

## BULGE AND HALO KINEMATICS ACROSS THE HUBBLE SEQUENCE

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## ABSTRACT

The correlation between the maximum rotational velocity of the disk ( $v_m$ ) and the central stellar velocity dispersion of the bulge ( $\sigma_0$ ) offers insights into the relationship between the halo and the bulge. We have assembled integrated H I line widths and central stellar velocity dispersions to study the  $v_m$ – $\sigma_0$  relation for 792 galaxies spanning a broad range of Hubble types. Contrary to earlier studies based on much smaller samples, we find that the  $v_m$ – $\sigma_0$  relation exhibits significant intrinsic scatter and that its zeropoint varies systematically with galaxy morphology, bulge-to-disk ratio, and light concentration, as expected from basic dynamical considerations. Nucleated but bulgeless late-type spiral galaxies depart significantly from the  $v_m$ – $\sigma_0$  relation. While these results render questionable any attempt to supplant the bulge with the halo as the fundamental determinant of the central black hole mass in galaxies, the observed distribution of  $v_m/\sigma_0$ , which depends on both the density profile and kinematic structure of the galaxy, offers a useful constraint on galaxy formation models. With the aid of a near-infrared Tully-Fisher relation, we identify a population of otherwise normal, luminous galaxies that have exceptionally low values of  $v_m/\sigma_0$ . We argue that a significant fraction of the H I gas in these kinematically anomalous objects is dynamically unrelaxed, having been acquired externally either through capture from tidal interactions or through cold accretion from the intergalactic medium.

*Subject headings:* galaxies: bulges — galaxies: ISM — galaxies: kinematics and dynamics — galaxies: nuclei

## 1. INTRODUCTION

It is accepted that every galaxy contains an extended dark matter halo, but precisely how the halo couples to the luminous components of the galaxy remains a subject of lively debate. Much attention has been given to the connection between the disk and the halo, in particular as it concerns the fraction of baryons that collapse to form the disk and the role of adiabatic contraction (e.g., Navarro & Steinmetz, 2000; Dutton et al. 2007). In disk galaxies that contain bulges, what is the relationship between the bulge and the halo? While a variety of methods can be used to address this question, important insights can be gained by investigating the relation between the line-of-sight central stellar velocity dispersion of the bulge,  $\sigma_0$ , and the deprojected maximum rotation velocity of the disk,  $v_m$ , which effectively traces the circular velocity of the halo. Whitmore and collaborators (Whitmore et al. 1979; Whitmore & Kirshner 1981) first looked into this issue, using a small sample of spiral galaxies for which they had  $\sigma_0$  and  $v_m$  measured through integrated H I velocity profiles. They find  $v_m/\sigma_0 \approx 1.2$  to 2, with the ratio increasing with decreasing bulge-to-disk ratio; elliptical galaxies roughly follow the same pattern (Fall 1987; Franx 1993). These trends were subsequently confirmed for a larger sample of normal (Whittle 1992a) and Seyfert (Nelson & Whittle 1996) galaxies.

The  $v_m$ – $\sigma_0$  relation recently has attracted renewed attention in the context of black hole demographics studies. The interest is three-fold. First, if  $\sigma_0$  is related to  $v_m$ , then the existence of the  $M_{\text{BH}}$ – $\sigma_0$  relation (Gebhardt et al. 2000; Ferrarese & Merritt 2000) suggests that the black hole mass may be more fundamentally tied to the halo mass rather than the bulge mass. This is the argument made by Ferrarese (2002), who revisited the  $v_m$ – $\sigma_0$  correlation originally introduced by Whitmore and collaborators. Second, apart from its theoretical implications, the existence of a  $v_m$ – $\sigma_0$  correlation presents a new empirical tool

for black hole demographics studies. Stellar velocity dispersions are not always easy or even possible to obtain, especially for active galaxies, whose bright nonstellar nuclei often overwhelm the stellar continuum and make measurement of central stellar velocity dispersions exceedingly challenging (e.g., Greene & Ho 2006). In such circumstances, it may be more feasible to measure  $v_m$  for the disk, either through spatially resolved rotation curves or integrated H I line profiles (Ho et al. 2007a). Finally, the  $v_m$ – $\sigma_0$  correlation represents a new scaling relation for galaxies, which, like other more familiar scaling relations, serves as an important boundary condition for theoretical models of galaxy formation.

Ferrarese (2002) compiled kinematic data for 16 disk (spiral and S0) galaxies with dynamical determinations of black hole masses to show that the rotation velocity of the disk, measured on the flat part of the rotation curve, follows a tight, nearly linear correlation with the central stellar velocity dispersion of the bulge. For her sample, the correlation breaks down for  $\sigma_0 \lesssim 80 \text{ km s}^{-1}$ . The 19 elliptical galaxies with rotation velocities derived from the dynamical models of Kronawitter et al. (2000) and Gerhard et al. (2001) seem to fall on the same correlation, suggesting that the  $v_m$ – $\sigma_0$  relation is universally obeyed by galaxies of all types. This result was echoed in subsequent studies (Baes et al. 2003), some of which (Pizzella et al. 2005; Buyle et al. 2006) additionally suggested that low-surface brightness galaxies follow a separate, nearly parallel relation compared to high-surface brightness galaxies by having a larger  $v_m$  for a given  $\sigma_0$ . In the most comprehensive analysis to date, Courteau et al. (2007) challenged the existence of a tight, Hubble type-invariant  $v_m$ – $\sigma_0$  relation. Instead, their enlarged sample clearly demonstrates that  $v_m/\sigma_0$  systematically varies with the concentration of the galaxy light profile, a result already apparent in the original work of Whitmore and others.

This paper examines the  $v_m$ – $\sigma_0$  correlation using an extensive sample of nearby galaxies with accurate measurements of

TABLE 1: THE SAMPLE

Galaxy	$T$	Bar	$C_{59}$	$b/a$	Ref.	$i$ (deg.)	$v_{\text{helio}}$ (km s $^{-1}$ )	$D_L$ (Mpc)	$M_{B_T^c}$ (mag)	$M_{K_s}$ (mag)	$\log M_{\text{H I}}$ ( $M_{\odot}$ )
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
ESO 097–013	3.3	N	...	0.44	1	68.2	437	4.5	−19.11	−23.28	9.46
ESO 186–055	2.0	N	...	0.43	1	71.0	4708	64.5	−20.02	−23.04	...
ESO 189–007	3.8	Y	...	0.72	1	45.2	2982	39.5	−22.31	−24.03	10.16
ESO 206–014	5.0	Y	...	0.83	1	34.5	15000	210.5	−22.47	−23.65	...
ESO 215–039	4.8	Y	...	0.71	1	46.2	4348	59.1	−21.32	−23.29	9.66

NOTE.— Col. (1) Galaxy name. Col. (2) Morphological type index. Col. (3) Presence of a bar. Col. (4) The concentration index in the  $i$  band, defined as  $C_{59} = 5 \log(r_{\text{P90}}/r_{\text{P50}})$ , where  $r_{\text{P90}}$  and  $r_{\text{P50}}$  are the Petrosian radii enclosing 90% and 50% of the light, respectively. Col. (5) Ratio of semi-minor to semi-major axis isophotal diameter measured at a surface brightness of  $\mu_B = 25$  mag arcsec $^{-2}$ . Col. (6) Reference for  $a$  and  $b$ . Col. (7) Inclination angle, calculated from  $b/a$ , as described in the text. Col. (8) Heliocentric velocity. Col. (9) Luminosity distance, derived assuming a Local Group infall velocity of 208 km s $^{-1}$  toward the Virgo cluster and a Hubble constant of  $H_0 = 70$  km s $^{-1}$  Mpc $^{-1}$ . Additional data come from Rizzi et al. 2006 (NGC 300), Lee et al. 2002 (NGC 598), Thim et al. 2004 (NGC 4395), and Karachentsev et al. 2003 (NGC 7793). Col. (10) Total absolute  $B$ -band magnitude, corrected for Galactic and internal extinction, using the inclination angle from Col. (7) and the formalism of Bottinelli et al. 1995. Col. (11) Total absolute  $K_s$ -band magnitude from 2MASS; these values have not been corrected for Galactic or internal extinction. Col. (12) H I mass, calculated using the following prescription from the RC3,  $\log(M_{\text{H I}}/M_{\odot}) = -0.4m_{21} + \log(1+z) + 2\log(D_L/\text{Mpc}) + 12.3364$ , where  $m_{21}$  is the H I “flux” and  $z$  is the redshift. Data for Cols. (2), (3), (8), (10), and (12) are taken from HyperLeda. *Table 1 is presented in its entirety in the electronic edition of the Astrophysical Journal. A portion is shown here for guidance regarding its form and content.*

REFERENCES.— (1) RC3; (2) Nilsen 1973; (3) Paturel et al. 2000; (4) Freudling et al. 1992; (5) Vorontsov-Velyaminov et al. 1963; (6) MacGillivray et al. 1988; (7) Haynes et al. 1997; (8) HyperLeda; (9) Binggeli et al. 1985.

both central stellar velocity dispersions and disk rotation velocities derived from integrated H I line widths. Our sample is significantly larger than those employed in recent studies, and it covers galaxies spanning a very wide range in Hubble types, allowing us to investigate trends with bulge-to-disk ratio. This analysis is similar in spirit to that of Courteau et al. (2007), the main difference being that ours utilizes integrated H I line widths instead of resolved rotation curves to estimate  $v_m$ , a shortcut that enables us to dramatically increase the sample size.

We confirm, with greater statistical weight, that the  $v_m$ – $\sigma_0$  relation systematically depends on the galaxy luminosity density profile, parameterized by Hubble type, bulge-to-disk ratio, or concentration index, and that there exists significant intrinsic scatter at a given density. This finding does not bode well for attempts to use galaxy rotation velocities to predict black hole masses, nor does it support the contention that the black hole mass is more fundamentally linked to the halo than the bulge, but it does offer a new, potentially powerful constraint on galaxy formation models. We draw attention to a subset of galaxies characterized by having exceptionally narrow H I profiles for their central stellar velocity dispersion. We suggest that the neutral hydrogen in these systems lies in a plane offset from that of the stellar disk, or that it has not yet settled into dynamical equilibrium with the stars.

## 2. DATA COMPILATION

Our goal is to compile as large a collection of galaxies as possible having relatively homogeneous, well-documented measurements of central stellar velocity dispersions and rotational

velocities that probe the flat part of the disk rotation curve. Apart from the sample size, a key difference between our analysis and those of previous studies [with the exception of initial work by Whitmore et al. (1979), Whitmore & Kirshner (1981), Whittle (1992a), and Nelson & Whittle (1996)] is that our values of  $v_m$  come from spatially integrated (single-dish) H I profiles. Previous authors have stressed the importance of measuring  $v_m$  from spatially resolved, extended optical spectra that sample the flat part of the rotation curve. Here we wish to emphasize that integrated H I line widths provide a robust and efficient substitute for estimating  $v_m$ . This has been well-documented in numerous studies, many motivated by the desire to use H I line widths for distance-scale investigations using the Tully-Fisher (Tully & Fisher 1977) relation (e.g., Rubin et al. 1978; Thonnard 1983; Mathewson et al. 1992; Courteau 1997). The global H I line width imprints both the shape of the galaxy’s rotation curve and the actual spatial distribution of the neutral hydrogen. But since the H I distribution in spiral galaxies typically extends to twice the optical radius (Broeils & Rhee 1997; Noordermeer et al. 2005), in practice the width of the H I velocity profile is quite robust to different rotation curves and H I distributions (Roberts 1978).

We have compiled a database that consists of four samples, which we describe in turn.

- *Sample 1* — The primary source of data for our investigation comes from HyperLeda<sup>1</sup> (Paturel et al. 2003a). This catalog is periodically updated, and the entries used in the present analysis are reported to be current up to the end of 2003. The stellar velocity dispersions in

<sup>1</sup> <http://leda.univ-lyon1.fr>

TABLE 2: KINEMATICAL DATA

Galaxy	Sample	$\sigma_0$ (km s <sup>-1</sup> )	error (km s <sup>-1</sup> )	$W_{20}$ (km s <sup>-1</sup> )	$W_{50}$ (km s <sup>-1</sup> )	$v_m$ (km s <sup>-1</sup> )	error (km s <sup>-1</sup> )	Rad. ( <sup>o</sup> )	Tel.	Ref.	Notes
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
ESO 097–013	1	157.6	18.8	283.8	242.1	115.1	8.8	14.5	10	1	...
ESO 186–055	4c	92.0	2.0	...	...	242.8	11.0	...	...	...	...
ESO 189–007	4a	91.0	2.0	317.0	295.1	178.7	14.7	14.5	10	1	...
ESO 206–014	4c	54.0	2.0	...	...	199.9	5.0	...	...	...	...
ESO 215–039	4a	71.0	11.0	267.9	215.8	132.2	4.7	14.5	10	2	...

NOTE.— Col. (1) Galaxy name. Col. (2) Sample. Col. (3) Central stellar velocity dispersion. Col. (4) Error on  $\sigma_0$ . Col. (5) Width of the H I profile at 20% of the maximum peak. Col. (6) Width of the H I profile at 50% of the maximum peak. Col. (7) Maximum rotation velocity  $v_m$ , corrected for instrumental resolution, interstellar turbulence,  $(1+z)$  cosmological stretching, and inclination angle. We obtained  $v_m$  from either  $W_{20}$  or  $W_{50}$  using the calibration given in Paturel et al. 2003b; when both  $W_{20}$  and  $W_{50}$  are available,  $v_m$  is the average of the two derived values. Col. (8) Error on  $v_m$ , assumed to be approximated by the error on the homogenized value of the rotation velocity given in HyperLeda. Col. (9) Radius searched for interlopers and confusing sources. Col. (10) Telescope used to obtain the H I data: (1) Nançay; (2) Westerbork Synthesis Radio Telescope; (3) NRAO Green Bank 140 foot; (5) Jodrell Bank 76 m; (7) NRAO Green Bank 300 foot; (8) Effelsberg 100 m; (9) Arecibo; (10) Parkes 64 m; (14) Jodrell Bank 125 foot×85 foot; (15) Very Large Array. Col. (11) Reference for the H I data. Col. (12) Notes: (1) Faint galaxy in the beam, but unlikely to be a source of confusion. (2) Significant galaxy in the beam, but not a source of confusion according to interferometric data. *Table 2 is presented in its entirety in the electronic edition of the Astrophysical Journal. A portion is shown here for guidance regarding its form and content.*

REFERENCES.— (1) Koribalski et al. 2004; (2) Mathewson & Ford 1996; (3) Paturel et al. 2003b; (4) Theureau et al. 1998; (5) Mould et al. 1991; (6) Haynes et al. 1997; (7) Fisher & Tully 1981; (8) Chamaraux et al. 1990; (9) Peterson 1979; (10) Bica & Giovanelli 1987; (11) Mould et al. 1993; (12) Richter & Huchtmeier 1987; (13) Lewis et al. 1985; (14) Haynes & Giovanelli 1984; (15) Williams 1985; (16) Eder et al. 1991; (17) Theureau et al. 2005; (18) Haynes et al. 1999; (19) Bothun et al. 1985; (20) Bica & Giovanelli 1986a; (21) Richter & Huchtmeier 1991; (22) Bica & Giovanelli 1986b; (23) Williams & Kerr 1981; (24) Hoffman et al. 1989; (25) Hoffman et al. 1985; (26) Giovanelli et al. 1997; (27) van Driel et al. 2000; (28) Freudling et al. 1992; (29) Reif et al. 1982; (30) Giovanelli & Haynes 1993; (31) Bottinelli et al. 1982; (32) Dean & Davies 1975; (33) Lu et al. 1993; (34) Wegner et al. 1993; (35) Nordgren et al. 1998; (36) Huchtmeier 1973; (37) Giovanardi et al. 1983; (38) Bottinelli et al. 1999; (39) Dickel & Rood 1978; (40) Magri 1994; (41) Huchtmeier et al. 1995; (42) Giovanardi & Salpeter 1985; (43) Impey et al. 2001; (44) Fosbury et al. 1978; (45) Giovanelli & Haynes 1985; (46) Haynes et al. 1988; (47) Staveley-Smith & Davies 1987; (48) Bregman et al. 1992; (49) Staveley-Smith & Davies 1988; (50) Bottinelli et al. 1980; (51) Sulentic & Arp 1983; (52) Schneider et al. 1986; (53) Krumm & Salpeter 1980; (54) Rosenberg & Schneider 2000; (55) Dell’Antonio et al. 1996; (56) Lewis 1987; (57) Huchtmeier & Richter 1987; (58) Mirabel & Wilson 1984; (59) Huchtmeier & Richter 1985; (60) Haynes 1981; (61) Huchtmeier 1982; (62) Huchtmeier & Seiradakis 1985; (63) Davis & Seaquist 1983; (64) Tift & Cocke 1988; (65) Balkowski & Chamaraux 1981; (66) Lewis & Davies 1973; (67) Knapp et al. 1979; (68) Williams & Rood 1987; (69) Bieging & Biermann 1977; (70) Mirabel & Sanders 1988; (71) Bosma 1979; (72) Burstein et al. 1987; (73) Haynes & Giovanelli 1991; (74) Schneider et al. 1990; (75) Bottinelli & Gougouenheim 1977; (76) Balkowski & Chamaraux 1983; (77) Bottinelli & Gougouenheim 1979; (78) Knapp et al. 1985; (79) Freudling 1995; (80) Verheijen & Sancisi 2001; (81) Helou et al. 1984; (82) Haynes et al. 1990; (83) García-Barreto et al. 1994; (84) Kraan-Korteweg et al. 1999; (85) Bregman & Roberts 1988; (86) Davies & Lewis 1973; (87) Giovanelli & Haynes 1983; (88) Helou et al. 1981; (89) Knapp et al. 1978; (90) van Driel et al. 2000; (91) Hoffman et al. 1987; (92) Krumm & Salpeter 1976; (93) Roth et al. 1994; (94) Gavazzi 1987; (95) Rubin et al. 1976; (96) Garcia et al. 1994; (97) Chamaraux et al. 1987; (98) van Driel et al. 2001; (99) Haynes & Giovanelli 1991; (100) Staveley-Smith et al. 1992; (101) Roth et al. 1991; (102) Schneider et al. 1992; (103) Chengalur et al. 1994; (104) Lewis 1983; (105) Barnes et al. 1997; (106) Freudling et al. 1988; (107) Lu et al. 1990; (108) Hewitt et al. 1983; (109) Oosterloo & Shostak 1993; (110) Thuan et al. 1999; (111) Irwin & Seaquist 1991; (112) Huchtmeier et al. 1997; (113) Giovanelli & Haynes 1985; (114) Matthews et al. 2001; (115) Giovanelli et al. 1981; (116) Thuan & Martin 1981; (117) Schombert et al. 1992; (118) Martin et al. 1991; (119) Heckman et al. 1978; (120) Matthews & van Driel 2000; (121) Salzer 1992; (122) Jackson et al. 1987; (123) Fontanelli 1984; (124) Bothun et al. 1984; (125) Richter & Huchtmeier 1982.

Hyperleda have been “homogenized” following the precepts of McElroy (1995). Generally the measurements pertain to a central aperture that is smaller than the effective radius of the bulge. Although it is sometimes customary to scale the velocity dispersions to a fixed aperture (e.g., to  $R_{\text{eff}}/8$ ; Jørgensen et al. 1995), this practice assumes that all bulges possess a similar velocity dispersion profile, which, according to the observations of Pizzella et al. (2005), appears not to be the case. We thus use the central values of  $\sigma_0$ , which for our sample on average have uncertainties of 13%, with a standard

deviation of 11%.

Nearly all of the rotation velocities in Hyperleda are derived from spatially integrated H I line widths, homogenized in the manner described in Paturel et al. (2003b). Using extensive sets of galaxies that contain both integrated H I profiles and spatially resolved optical rotation curves, these authors determined the optimal transformation between the H I line width measured at different levels of the line peak (e.g., 20% or 50% of the maximum) and the maximum velocity of rotation. In this way, the archived H I measurements, which can be quite

voluminous for any given galaxy, can be standardized and reduced to a single value for the rotation velocity. Although this procedure is clearly very useful, following the spirit in which the stellar velocity dispersions themselves were treated, unfortunately the rotation velocities listed in Hyperleda cannot be used at face value because of the possibility of source confusion. Single-dish H I measurements subtend over a significant beam area, typically from  $3.5'$  for the Arecibo telescope to as much as  $22'$  for the Nançay telescope, within which there is a nonnegligible probability of contamination from interlopers or neighboring galaxies. Hyperleda does *not* take this crucial effect into consideration prior to homogenizing the H I data.

Accordingly, we have taken the following steps to cull the data. Beginning with an initial sample of  $\sim 1500$  galaxies having both velocity dispersions and H I measurements, for each galaxy we systematically inspected the list of H I line widths given in Hyperleda. In this process, we give preference to more modern observations if available, to data taken with the highest spectral resolution, to line width measurements that pertain to either the 20% or 50% of the maximum of the line profile (preferably both), and, whenever possible, we try to minimize the heterogeneity of the sample by favoring larger, more systematic surveys. For each galaxy, we identify what we deem to be the most robust line width measurement taken with the *smallest* available beam, where robustness is judged by whether the line width has reached a stable, asymptotic value when data from multiple telescopes are listed. We then carefully examined digital optical images, from the SDSS if available or else from the scanned images of the Palomar Digital Sky Survey, in combination with redshift information listed in the NASA/IPAC Extragalactic Database (NED)<sup>2</sup> to eliminate potential sources of confusion within a radius equal to the full-width at half power of the beam of the chosen telescope (see Table 2). For observations taken with the Arecibo telescope, the search radius was increased to  $7.5'$  to account for the extended sidelobes of the beam; the intensity of the first sidelobes of the beam drops to  $\sim 10\%$  of the peak at a distance of  $5.5'$  from the beam center, and by  $7'-8'$  it becomes negligible (Heiles et al. 2000). A number of galaxies contain faint, low-surface brightness companions that formally lie within the H I beam, but generally such companions can be ruled out as sources of confusion because of their low luminosities (they would otherwise grossly violate the Tully-Fisher relation given the large line widths). Galaxies that are likely to be confused are flagged and omitted from the sample. We retained a few galaxies that, although potentially confused within the single-dish beam, have line widths consistent with the velocity amplitude measured in interferometer maps, which suggest that confusion is not a problem. To avoid complications in the interpretation of their H I kinematics, we also removed galaxies known to be merger remnants or that, from our visual inspection, otherwise possess disturbed morphologies, tidal tails, shells, or polar rings. We do not consider dwarf irregular galaxies ( $T \geq 9.0$ ) because they are un-

likely to have trustworthy central stellar velocity dispersion measurements or unambiguous bulges. The above selection reduced the Hyperleda sample to 293 galaxies.

- *Sample 2* — Many galaxies in Hyperleda have usable H I line widths but no stellar velocity dispersion in the database. A significant number of them overlap with the Sloan Digital Sky Survey (SDSS; York et al. 2000), and stellar velocity dispersions for 435 of these have been measured and made publically available by D. J. Schlegel<sup>3</sup>. In this selection, we only retain galaxies that have velocity dispersions larger than the spectral instrumental resolution of SDSS ( $\sim 70 \text{ km s}^{-1}$ ) and that satisfy our morphological type cut ( $T < 9.0$ ). We visually examined the SDSS spectrum of every object to confirm that the reported velocity dispersion is sensible; a number of spurious values, almost all resulting from erroneous fitting of noisy spectra of faint, dwarf galaxies, were rejected during this process. D. J. Schlegel et al. (2007, in preparation; see also Heckman et al. 2004) measure velocity dispersions using a direct-fitting algorithm and template stars from a library of echelle stellar spectra. The Appendix presents an external comparison of the velocity dispersions given in SDSS with those published in Hyperleda, for objects in common between samples 1 and 2. The SDSS values are on average 12% larger than those in Hyperleda.
- *Sample 3* — The issue of whether  $\sigma_0$  or  $v_m$  more fundamentally tracks  $M_{\text{BH}}$  can be most effectively addressed by using extremely late-type spirals that essentially lack a bulge altogether (Böker et al. 2003) and rarely contain a central black hole (see discussion in §4.1). While rotational velocities can be measured readily in these gas-rich systems, obtaining accurate central stellar velocity dispersions for them is extremely challenging because of the faintness or absence of a central spheroidal component. We can place a useful limit on the “bulge” velocity dispersion of such systems by measuring the dispersion of its central nuclear star cluster, which is commonly found (Böker et al. 2002). These are challenging observations, because the clusters are faint and the dispersions are small, requiring echelle resolution on large telescopes. We have been able to locate suitable  $\sigma_0$  measurements for a total of 10 late-type, bulgeless spirals: NGC 598 (M33; Kormendy & McClure 1993), NGC 4395 (Filippenko & Ho 2003), and eight galaxies from the Böker et al. (2002) survey (Walcher et al. 2005).
- *Sample 4* — Courteau et al. (2007) give the latest compilation of galaxies having both  $\sigma_0$  and  $v_m$  determined largely from extended optical rotation curves [59 of their objects come from the study of Prugniel et al. (2001), whose measurements of  $v_m$  were derived from H I line widths]. Of the 164 galaxies in Courteau’s compilation, 54 are not included in our samples 1–3; these form the last sample in our study. We distinguish three subsets: (a) 21 galaxies with  $\sigma_0$  taken from Courteau et al. and

$v_m$  derived from H I line widths in Hyperleda; (b) 26

<sup>2</sup><http://nedwww.ipac.caltech.edu/>

<sup>3</sup><http://spectro.princeton.edu>

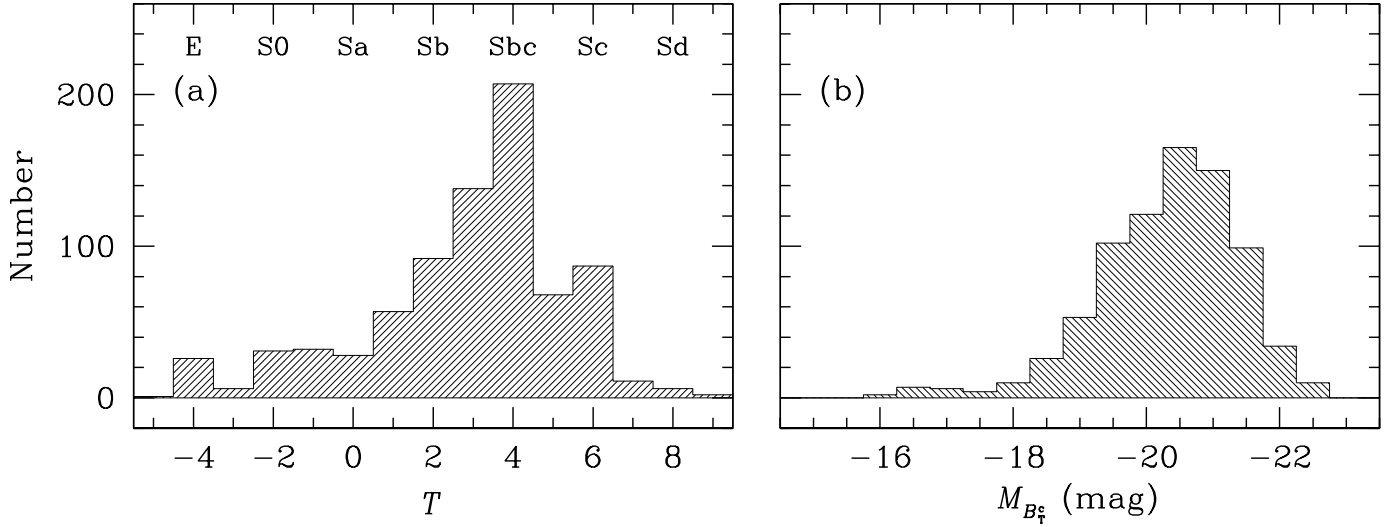


FIG. 1.— Distribution of (a) morphological type index  $T$  and (b) total  $B$ -band absolute magnitude, corrected for Galactic and internal extinction, for the 792 galaxies in our sample. A rough mapping between  $T$  and Hubble type is given on the upper abscissa of panel (a).

galaxies with  $v_m$  taken from Courteau et al. and  $\sigma_0$  taken from Hyperleda; and (c) 7 galaxies with  $\sigma_0$  and  $v_m$  both taken from Courteau et al. In the interest of maximizing the homogeneity of our combined sample, we have decided to use H I line widths whenever available even if Courteau et al. give  $v_m$  from resolved rotation curves. Similarly, we give preference to the  $\sigma_0$  values in Hyperleda because these represent weighted averages of all available literature measurements, and they have been scaled to a common system adopted for the rest of our study. The velocity dispersions that overlap between Courteau and Hyperleda show excellent agreement, with Courteau's values on average 3% higher than Hyperleda's.

The combination of the above four samples produces a final compilation of 792 galaxies, summarized in Figure 1 and Tables 1 and 2. Most of the galaxies are nearby (median distance 23 Mpc) and luminous (median  $M_{B_T} = -20.3$  mag), spanning the entire range of Hubble types, from giant ellipticals to late-type spirals (morphological type index  $T = -5$  to 8).

The published H I line widths have been corrected for instrumental resolution but not for  $(1+z)$  cosmological stretching or for broadening by interstellar turbulence. A number of authors have discussed the impact of turbulence on the line width measurements (e.g., Tully & Fouqué 1985; Fouqué et al. 1990). Given the demographic make up of most of our sample (Fig. 1b), we adopt the simple linear subtraction recommended by Bottinelli et al. (1983) for giant galaxies,

$$W = W_{\text{obs}} - W_{\text{turb}}, \quad (1)$$

where  $W_{\text{obs}}$  is the observed line width (at either 20% or 50% of the maximum), and the turbulent velocity is taken to be  $W_{\text{turb}} = 22 \text{ km s}^{-1}$  for  $W_{20}$  and  $W_{\text{turb}} = 5 \text{ km s}^{-1}$  for  $W_{50}$  (Verheijen & Sancisi 2001).

As the H I line widths must be deprojected along the line-of-sight, we need to pay careful attention to the adopted inclination angle. Although Hyperleda conveniently lists inclina-

tion angles for our sample, they differ systematically and sometimes dramatically from the values given in other catalogs (see Appendix). We therefore resorted to recompiling our own axial ratios and recalculating the inclination angles for the entire sample (Table 1). We derive the inclination angle  $i$  using Hubble's (1926) formula,

$$\cos^2 i = \frac{q^2 - q_0^2}{1 - q_0^2}, \quad (2)$$

which makes use of the apparent flattening of the galaxy ( $q \equiv b/a$ ) as measured from the ratio of its semi-minor and semi-major isophotal diameters at a surface brightness of  $\mu_B = 25 \text{ mag arcsec}^{-2}$ , assuming that the intrinsic thickness of the disk ( $q_0$ ) depends on morphological type as given in Paturel et al. (1997). To mitigate against large uncertainties inherent in determining the inclination angle of nearly face-on systems, throughout this paper we remove galaxies that have inclination angles of  $i < 30^\circ$ ; these account for  $\sim 10\%$  of the original sample. An important caveat, however, is that for most of the galaxies in our study we have absolutely *no* information on the spatial distribution of the neutral hydrogen. Given that some H I disks can be misaligned with respect to the stellar distribution (e.g., Lewis 1987), our optically derived inclination correction may not be valid in some instances. Another source of uncertainty comes from strong warps and other types of nonaxisymmetric distortions in the H I disk, which are known to be present in many disk galaxies (e.g., Baldwin et al. 1980; Bosma 1981; Lewis 1987; Richter & Sancisi 1994; Haynes et al. 1998). Indeed, in §4.3 we present evidence based on our sample that a sizable fraction of nearby galaxies may have strongly disturbed or dynamically unrelaxed H I distributions.

Lastly, we need an empirical prescription to convert the corrected H I line width into the maximum rotation velocity. This issue has been investigated in a number of studies (e.g., Mathewson et al. 1992; Courteau 1997), the latest and most thorough being that of Paturel et al. (2003b), whose calibrations we adopt. In detail, the calibrations depend on the resolution of the

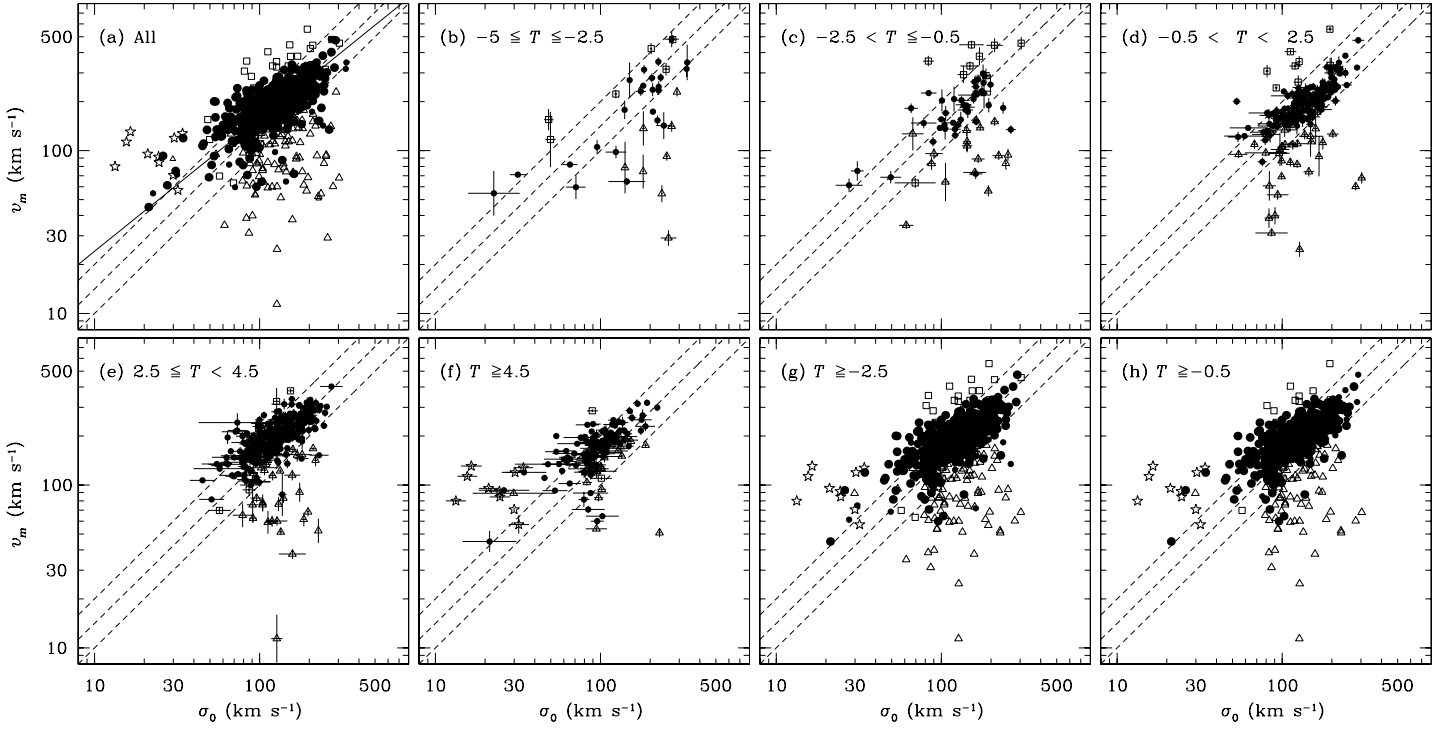


FIG. 2.— The relationship between central stellar velocity dispersion and the maximum rotation velocity for galaxies of the following Hubble types: (a) all, (b) ellipticals ( $-5 \leq T \leq -2.5$ ), (c) S0 ( $-2.5 < T \leq -0.5$ ), (d) Sa–Sb ( $-0.5 < T < 2.5$ ), (e) Sbc–Sc ( $2.5 \leq T < 4.5$ ), (f) later than Sc ( $T \geq 4.5$ ), (g) all disks, and (h) all spirals. Sources that are low-velocity and high-velocity outliers in the Tully–Fisher relation (Fig. 3) are plotted as open triangles and squares, respectively. The solid points belong to the “kinematically normal” sample. In panels (a) and (f)–(h), the extreme late-type, bulgeless spirals are plotted as stars. For the sake of clarity, error bars are not shown in panels (a), (g), and (h). The dashed lines denote, from bottom to top,  $v_m = \sigma_0$ ,  $\sqrt{2} \sigma_0$ , and  $\sqrt{4} \sigma_0$ . The best fit to the entire sample of kinematically normal galaxies is plotted as a solid line in panel (a).

observations, but for simplicity we just use those obtained for the highest resolution ( $8 \text{ km s}^{-1}$ ):

$$\log 2v_m \sin i = (1.071 \pm 0.009) \log W_{50} - (0.210 \pm 0.023)$$

$$\log 2v_m \sin i = (1.187 \pm 0.002) \log W_{20} - (0.543 \pm 0.005). \quad (3)$$

The uncertainty on  $v_m$  is taken to be the value formally given in Hyperleda. This is a conservative estimate because in many cases the Hyperleda value incorporates a larger spread of individual measurements than we actually used. For our sample, the values of  $v_m$  have an average uncertainty of 6.3%, with a standard deviation of 5.4%.

### 3. THE $v_m$ – $\sigma_0$ RELATION

Figure 2 summarizes our principal findings. Taken collectively (Fig. 2a), the distribution of  $v_m$  versus  $\sigma_0$  shows, at best, a loose correlation. Although the best-fit relations of Baes et al. (2003) or Pizzella et al. (2005) roughly bisect the cloud of points, the scatter is enormous, far greater than can be attributed to observational errors or potential sources of systematic uncertainty (e.g., inclination corrections for  $v_m$  or aperture corrections for  $\sigma_0$ ). Separating the sample by Hubble type (Fig. 2b–2f) reveals three main culprits for the large scatter: (1) a systematic shift of zeropoint as a function of Hubble type, most clearly seen in the locus of the ridgeline defining the upper envelope of the distribution of points; (2) the existence of subset of low- $\sigma_0$  ( $\sigma_0 \lesssim 50 \text{ km s}^{-1}$ ), extreme late-type galaxies ( $T \approx 6-9$ , Hubble types Scd–Sdm) that have almost constant  $v_m$  ( $\sim 100 \text{ km}$

$\text{s}^{-1}$ ); and (3) a cloud of points, present in all Hubble type bins, but especially prominent for earlier-type systems, with very low values of  $v_m/\sigma_0$  (plotted as *open triangles*).

To assess how much of the scatter in the  $v_m$ – $\sigma_0$  diagram is intrinsic, we make use of the Tully–Fisher relation to constrain what value of  $v_m$  any particular galaxy *ought* to have given its luminosity. Since the Hubble type mix of a sample affects the slope, normalization, and scatter of the Tully–Fisher relation (e.g., Roberts 1978; Rubin et al. 1985; Bell & de Jong 2001; De Rijcke et al. 2007; Pizagno et al. 2007), and the variations are minimized in the near-infrared (e.g., Verheijen 2001), we assembled  $K_s$ -band ( $2.16 \mu\text{m}$ ) magnitudes for nearly the entire sample using the Extended Source Catalog of the Two-Micron All-Sky Survey (2MASS; Skrutskie et al. 2006). The photometry pertains to the “total” magnitudes (Table 1), and for simplicity we do not correct for Galactic or internal extinction, which should be quite small in the  $K_s$  band. Figure 3 shows that a  $K_s$ -band Tully–Fisher relation exists for all Hubble types, including E and S0, and, importantly in the present context, that there is little obvious variation in the slope, normalization, or scatter of the relation across the wide range of Hubble types included in our sample. Overplotted on the figure is the fit derived by Verheijen (2001) for the  $K'$  band, which is quite similar to the 2MASS  $K_s$  band (Bessel 2005). While the observed scatter of our Tully–Fisher relation is larger than that found by Verheijen (2001), a result that can be anticipated considering the larger distance errors and greater heterogeneity of our sample, most of our objects (625/792 or 70%; *solid points*) fall comfortably within the boundaries that enclose twice the rms scatter

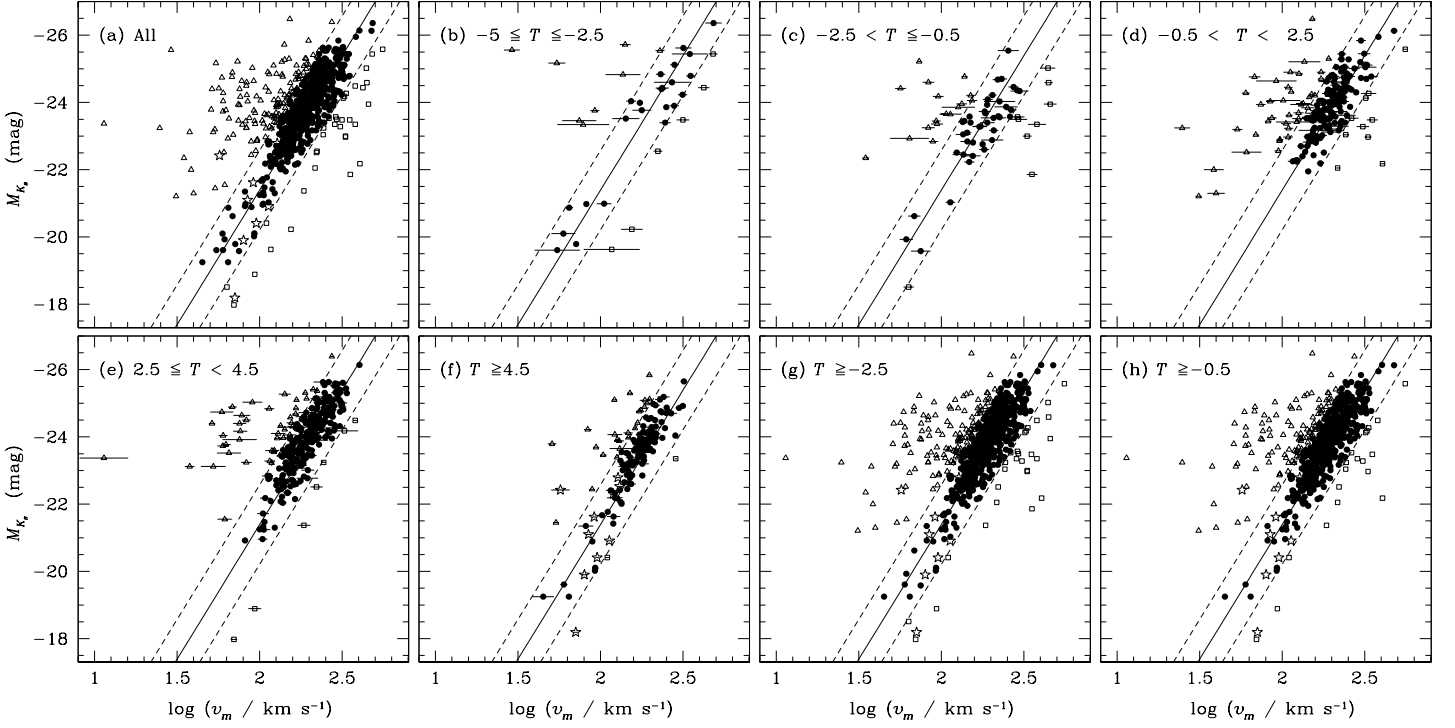


FIG. 3.— Tully-Fisher relation in the  $K_s$  band for galaxies of the following Hubble types: (a) all, (b) ellipticals ( $-5 \leq T \leq -2.5$ ), (c) S0 ( $-2.5 < T \leq -0.5$ ), (d) Sa–Sb ( $-0.5 < T < 2.5$ ), (e) Sbc–Sc ( $2.5 \leq T < 4.5$ ), (f) later than Sc ( $T \geq 4.5$ ), (g) all disks, and (h) all spirals. The *solid* line represents the  $K'$ -band Tully-Fisher relation from Verheijen (2001); the *dashed* lines mark the region that has twice the rms scatter. Sources that are low-velocity and high-velocity outliers are plotted as open triangles and squares, respectively; the solid points are considered to be the “kinematically normal” members of the sample. In panels (a) and (f)–(h), the extreme late-type, bulgeless spirals are plotted as stars. For the sake of clarity, error bars are not shown in panels (a), (g), and (h).

of Verheijen’s “H I” sample (0.59 mag); hereafter we will refer to these as the “kinematically normal” objects. Nevertheless, Figure 3 shows that there are a significant number of outliers, which we loosely and somewhat arbitrarily define to be those that lie outside of the 2-rms band. Closer inspection reveals that there is an *excess* of low-velocity objects (132/792 or 17%; *open triangles*) compared to high-velocity ones (35/792 or 4%; *open squares*). This is most obvious among the spirals ( $T \geq -0.5$ ) as a low- $v_m$  “plume,” but to a lesser extent it can be seen also among the E and S0 systems.

Within this backdrop, the distribution of points in the  $v_m$ – $\sigma_0$  diagram can now be more easily interpreted. The “kinematically normal” objects on the Tully-Fisher relation obey a loose correlation between  $v_m$  and  $\sigma_0$ , roughly occupying the region from  $v_m = \sigma_0$  to  $v_m = \sqrt{4}\sigma_0$ , depending on Hubble type. The correlation has significant scatter, and it is nonlinear. An ordinary least-squares bisector fit for the entire sample (Fig. 2a) yields

$$\log v_m = (0.82 \pm 0.027) \log \sigma_0 + (0.57 \pm 0.058), \quad (4)$$

very similar to the fit reported by Ferrarese (2002). There is no significant variation of the slope with Hubble type. Limiting the fit to the 550 kinematically normal spiral galaxies, the fit is nearly identical:

$$\log v_m = (0.80 \pm 0.029) \log \sigma_0 + (0.62 \pm 0.062). \quad (5)$$

The bulgeless late-type galaxies, which are largely kinematically normal in the Tully-Fisher relation, continue to depart notably from the rest of the sample in the  $v_m$ – $\sigma_0$  diagram. It is

of interest to note that the few late-type spirals (NGC 6140, NGC 6689, PGC 28990) that do host small bulges (as opposed to nuclear star clusters), along with some dwarf ellipticals and S0s (NGC 3870, NGC 7077, PGC 5441, PGC 71938), still follow the low-velocity extrapolation of the  $v_m$ – $\sigma_0$  relation. Within the large scatter, we find no compelling evidence for a break in the  $v_m$ – $\sigma_0$  relation at low velocities. Objects with low  $v_m/\sigma_0$  ( $\lesssim 1$ ) comprise almost exclusively the low-velocity outliers in the Tully-Fisher relation. The nature of the low- $v_m/\sigma_0$  objects is discussed further in §4.3. The high-velocity outliers, on the other hand, occupy the upper envelope of the  $v_m$ – $\sigma_0$  relation, especially for  $\sigma_0 \gtrsim 80 \text{ km s}^{-1}$ . Had these objects not been excluded, they would bias the  $v_m$ – $\sigma_0$  relation to a steeper slope.

Figure 4 highlights the trends with Hubble type more explicitly, showing the distribution of  $v_m/\sigma_0$  for six bins of morphological types. Although the binning of the morphological types is somewhat arbitrary, nevertheless the pattern is clear: as the Hubble type becomes later, the median of the distribution of  $v_m/\sigma_0$  systematically shifts to larger values, from  $\sim 1.2$  for ellipticals, to  $\sim 1.4$  for early-type spirals, to  $\sim 1.8$  for late-type spirals, and, very dramatically, to  $\sim 4.6$  for extreme late-type, bulgeless spirals. This trend was already largely noticed by earlier studies (Whitmore et al. 1979; Whitmore & Kirshner 1981; Franx 1993; Whittle 1992a; Zasov et al. 2005). Since we do not have reliable bulge-to-disk photometric decompositions for the majority of our sample, we constructed a surrogate measure of bulge luminosity for the disk galaxies by using the observed values of  $\sigma_0$  in combination with the Faber-Jackson (1976) relation. Using the 1072 elliptical ( $T \leq -2.5$ ) galaxies with measurements of  $\sigma_0$  listed in Hyperleda, we find the following

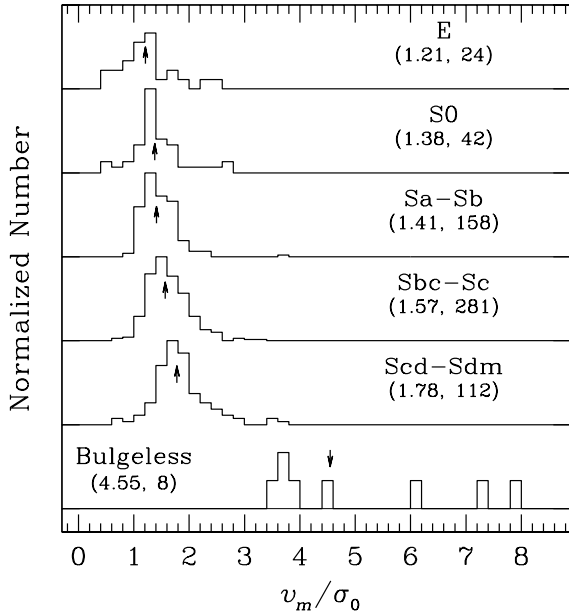


FIG. 4.— The distribution of the ratio of disk rotation velocity to bulge velocity dispersion for the “kinematically normal” galaxies (see §3) of Hubble type E, S0, Sa–Sb, Sbc–Sc, Scd–Sdm, and extreme late-type, bulgeless spirals. The median of each distribution is given, followed by the number of galaxies in the group; the median is also marked by an arrow.

ordinary least-squares bisector fit<sup>4</sup>:  $M_{B_T} = -6.80 \log \sigma_0 - 4.89$ . This method of estimating the “bulge” luminosity certainly has limitations. The Faber-Jackson relation for bulges is, as yet, not well-determined: it appears to differ systematically with Hubble type (Whitmore & Kirshner 1981; Kormendy &

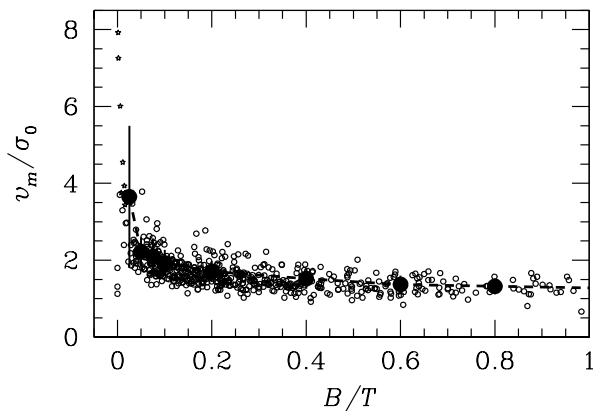


FIG. 5.— The variation of the ratio of disk rotation velocity to bulge velocity dispersion as a function of the bulge-to-total luminosity ratio. Here the “bulge” luminosity is calculated from the Faber-Jackson relation, as determined from a sample of 1072 elliptical galaxies in Hyperleda. The extreme late-type, bulgeless spirals are plotted as stars. The solid points connected by the dashed line show the mean and standard deviation of  $v_m/\sigma_0$  binned by  $B/T$  for the “kinematically normal” sources (see §3).

<sup>4</sup>This fit is roughly consistent with the SDSS results of Bernardi et al. (2003). For example, for a velocity dispersion of  $\sigma_0 = 200 \text{ km s}^{-1}$ , their equation (11) predicts  $M_g = -19.33 \text{ mag}$ , which, for  $g-B = -0.53 \text{ mag}$  expected for elliptical galaxies (Fukugita et al. 1995), translates to  $M_B = -18.80 \text{ mag}$ . Our fit gives  $M_B = -18.49 \text{ mag}$ .

<sup>5</sup>A small fraction of the sample, not shown in Figure 5, has  $B/T$  values that formally exceed unity. This should not be viewed as too alarming, in view of the indirect method by which we have estimated the “bulge” luminosity.

<sup>6</sup>Figure 6b contains fewer data points than Figure 2 of Courteau et al. (2007) because the latter treated repeat observations of the same objects as independent galaxies (S. Courteau 2006, private communications).

Illingworth 1983; but see Whittle 1992b) as well as between classical bulges and “pseudo-bulges” (Kormendy & Kennicutt 2004), and it shows significant intrinsic scatter within each Hubble type. Nevertheless, it is debatable whether these sources of systematic uncertainty are any more serious than the vagaries of photometric bulge-to-disk decomposition, especially for such a large and diverse sample of galaxies. With these caveats in mind, Figure 5 shows that  $v_m/\sigma_0$  clearly varies systematically with bulge-to-total ( $B/T$ ) luminosity ratio<sup>5</sup>. A given value of  $B/T$  can host a large range of  $v_m/\sigma_0$ , but on average  $v_m/\sigma_0$  increases as the prominence of the bulge component decreases, qualitatively consistent with the trends noted in Figures 2 and 4.

Another crude, but more direct, method to estimate the degree of bulge dominance is to calculate the “concentration index” of the light profile, which is roughly related to the bulge-to-disk ratio or Hubble type (e.g., Doi et al. 1993). The correlation between concentration index and Hubble type in the SDSS database has been investigated by Shimasaku et al. (2001) and Strateva et al. (2001). This is the approach taken by Courteau et al. (2007), who defined a concentration index  $C_{28} \equiv 5 \log(r_{80}/r_{20})$ , where  $r_{20}$  and  $r_{80}$  are the radii that enclose 20% and 80% of the total light, respectively. They computed  $C_{28}$  for 81 out of the 164 galaxies in their sample with available  $i$ -band images in the SDSS. We follow Courteau et al. in using the concentration index as a surrogate indicator for the density distribution of the galaxy light profile, but instead of  $C_{28}$ , we simply adopt the cataloged  $i$ -band Petrosian radii enclosing 50% ( $r_{p50}$ ) and 90% ( $r_{p90}$ ) of the light to form an equivalent concentration index  $C_{59} \equiv 5 \log(r_{p90}/r_{p50})$ . Not surprisingly,  $C_{28}$  and  $C_{59}$  are strongly correlated (Fig. 6a), albeit with significant scatter, which, too, is not unexpected. Figure 6b illustrates that substituting  $C_{59}$  for  $C_{28}$  faithfully recovers the correlation between  $v_m/\sigma_0$  and concentration index presented in Courteau et al. (2007; see their Fig. 2). If anything, using  $C_{59}$  instead of  $C_{28}$  seems to produce a diagram with even somewhat less scatter<sup>6</sup>.

The majority of our sample (76%) have photometric data available in the Fifth Data Release of SDSS (Adelman-McCarthy et al. 2007), and so we can calculate the  $C_{59}$  parameter for these objects (Table 1). As anticipated from the Courteau et al. study, Figure 7 illustrates that our sample indeed also behaves very similarly: a systematic trend exists between  $v_m/\sigma_0$  and  $C_{59}$ , although the scatter is substantial.

The density distribution, as traced by the morphological type, bulge-to-disk ratio, or concentration index, all of which are loosely mutually correlated, appears to be the dominant factor that determines a galaxy’s  $v_m/\sigma_0$  ratio. We have examined the total galaxy luminosity as a possible additional parameter, but it has little or no effect. This is not surprising, because with the exception of very late-type systems, a galaxy’s total luminosity shows only subtle variation with Hubble type (e.g., Roberts & Haynes 1994). A galaxy’s integrated broad-band colors ( $U-B$ ,  $B-V$ ,  $B-I$ ,  $B-K_s$ ), to the extent that they are available from Hyperleda, do show a moderate correlation with  $v_m/\sigma_0$ , but this is likely just a reflection of the dependence of galaxy color on



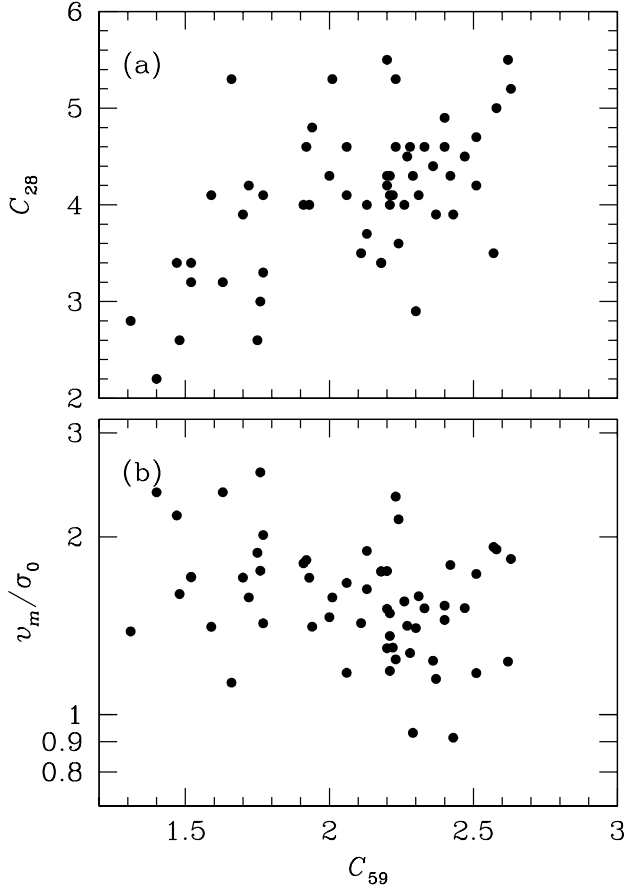


FIG. 6.— (a) The relation between  $i$ -band concentration indices as derived in the Petrosian system of SDSS,  $C_{59}$ , and as given by Courteau et al. (2007),  $C_{28}$ . The two concentration indices are strongly correlated. (b) The variation of  $v_m/\sigma_0$  with  $C_{59}$  for the sample of Courteau et al., plotted in the same fashion as Fig. 2 of Courteau et al., demonstrating that  $C_{59}$  can be substituted for  $C_{28}$ .

morphological type or concentration.

One caveat should be kept in mind. It is possible that the central velocity dispersions of the later-type galaxies are underestimated due to contamination by disk light. If so, this could mimic the variation of  $v_m/\sigma_0$  with galaxy type or bulge-to-disk ratio. This possibility needs to be checked with detailed spatially resolved stellar kinematical data.

#### 4. DISCUSSION

##### 4.1. Implications for Black Hole Demographics

This study was initiated with the intention of better quantifying the relation between disk rotation velocity and bulge stellar velocity dispersion, with the hope that such a correlation might be used as a new empirical tool to study the demographics of central black holes in galaxies. Earlier studies (Ferrarese 2002; Baes et al. 2003), based on relatively small samples with extended optical rotation curves, found that galaxies over a wide range of Hubble types, from mid-type spirals to giant ellipticals, obey a strong correlation between  $v_m$  and  $\sigma_0$  with almost no intrinsic scatter, at least for  $v_m \gtrsim 80 \text{ km s}^{-1}$ . Subsequent work has emphasized that the  $v_m$ – $\sigma_0$  relation may depend on surface brightness, with low-surface brightness galaxies lying systematically offset (larger  $v_m$  for a given  $\sigma_0$ ) from a still tight sequence defined by high-surface brightness galaxies (Pizzella et al. 2005; Buyle et al. 2006). If high-surface brightness galaxies truly do obey a tight  $v_m$ – $\sigma_0$  relation, one would have to

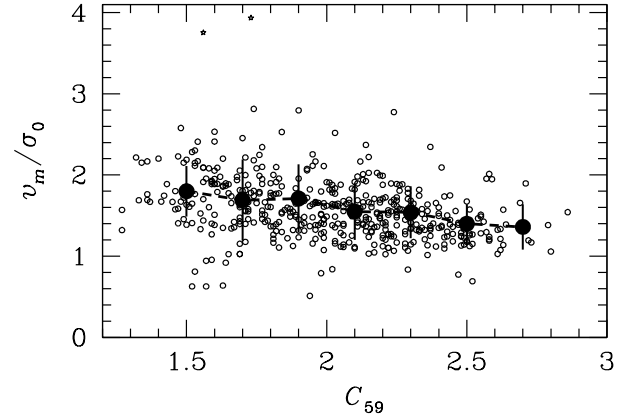


FIG. 7.— The variation of  $v_m/\sigma_0$  with the concentration index  $C_{59}$ . The extreme late-type, bulgeless spirals are plotted as stars. The solid points connected by the dashed line show the mean and standard deviation of  $v_m/\sigma_0$  binned by  $C_{59}$ , for the “kinematically normal” sources (see §3).

reevaluate which dynamical variable ( $\sigma_0$  or  $v_m$ ) or, equivalently, which structural component of the galaxy (bulge or halo) is more fundamentally related to black hole mass.

Nevertheless, there is reason to suspect that the  $v_m$ – $\sigma_0$  relation may not be as simple as had been claimed. Indeed, from the initial work of Whitmore and collaborators (Whitmore et al. 1979; Whitmore & Kirshner 1981), as well as from subsequent updates thereof (Fall 1987; Whittle 1992a; Franx 1993; Nelson & Whittle 1996), one could already have concluded that the ratio  $v_m/\sigma_0$  is *not* a constant, but rather that it varies systematically as a function of bulge-to-disk ratio, in the sense that early-type galaxies have characteristically smaller  $v_m/\sigma_0$  ratios than late-type galaxies. It was also apparent that there is significant scatter in  $v_m/\sigma_0$  for any given bulge-to-disk ratio. Baes et al. (2004) speculated that the culprit for the increased scatter could lie in Whitmore’s use of integrated H I line widths, which may not accurately trace the flat part of the rotation curve. This explanation, however, seems implausible in light of the long history of Tully–Fisher studies that have made use of integrated H I line widths, not to mention of the many comparisons made with optically derived rotation curves (e.g., Rubin et al. 1978; Thonnard 1983; Mathewson et al. 1992; Courteau 1997; Paturel et al. 2003b). Our own comparison shown in Figure 9, though limited, reinforces previous conclusions that integrated H I line widths serve as an effective proxy for rotation velocities measured from extended rotation curves, at least for spiral galaxies. Moreover, even if one were to admit that H I-based rotation velocities were less accurate, one would still have to explain why  $v_m/\sigma_0$  changes systematically with bulge-to-disk ratio. Zasov et al. (2005) provided further evidence that the  $v_m$ – $\sigma_0$  relation contains significant intrinsic scatter. Using a collection of 41 galaxies with black hole masses, central stellar velocity dispersions, and rotational velocities from *optical* rotation curves, these authors concluded that although  $M_{\text{BH}}$  does correlate with  $v_m$ , it is better correlated with  $\sigma_0$ . They also find that, at a given  $v_m$ , S0–Sab galaxies tend to have larger  $M_{\text{BH}}$  than later-type galaxies. From this, one can infer that earlier-type galaxies possess a smaller  $v_m/\sigma_0$  ratio than later-type galaxies. The latest demonstration that  $v_m/\sigma_0$  varies considerably and systematically with galaxy type comes from Courteau et al. (2007), whose  $v_m$  compilation—now increased to 164 galaxies—is also based largely on spatially resolved optical rotation curves.

Their study shows that the  $v_m$ - $\sigma_0$  relation exhibits marked scatter and that  $v_m/\sigma_0$  decreases steadily, albeit with large fluctuations, with increasing galaxy light concentration.

The present study evaluates the  $v_m$ - $\sigma_0$  relation with the largest sample to date, totaling 792 galaxies. This is made possible not only by access to a large number of new  $\sigma_0$  measurements from SDSS, but also by taking advantage of integrated H I line widths to estimate rotation velocities, a shortcut whose efficacy has been amply proved. As anticipated, we find that the  $v_m$ - $\sigma_0$  relation is far from tight. The zeropoint shifts systematically as a function of Hubble type, and within each Hubble type bin the scatter is at least a factor of 2–3. From the point of view of using  $v_m$  to predict  $M_{\text{BH}}$ , this is not promising, not if other properties of the host galaxy such as bulge luminosity (Kormendy & Gebhardt 2001; Marconi & Hunt 2003), and especially  $\sigma_0$  (Tremaine et al. 2002), are available. On the other hand, there are instances when the stellar component of the host galaxy can be extraordinarily challenging, if not impossible, to detect, either kinematically or photometrically. This is often the case in luminous active galactic nuclei or quasars. The host galaxy’s neutral hydrogen gas, by contrast, being immune to the bright glare of the active nucleus, may be more readily detectable with deep radio observations. Under these circumstances, an integrated line width, which can be extracted from an H I spectrum of even moderate signal-to-noise ratio, may be the *only* constraint available on the host galaxy. The recent analysis by Ho et al. (2007b) of a new H I survey of active galaxies (Ho et al. 2007a) demonstrates the rich body of information on the host galaxy that can be ascertained in this unique fashion. The existence of low- $v_m/\sigma_0$  outliers (§4.3) certainly complicates matters, but this difficulty is not insurmountable because these objects can be recognized as outliers in the Tully-Fisher relation, if an independent estimate of the total host galaxy luminosity can be estimated. Alternatively, Ho et al. (2007b) suggest that this kinematically anomalous population may have a greater tendency to exhibit single-peaked and/or highly asymmetric line profiles. While this trend still needs to be verified with better data, it may offer a very effective, practical strategy to weed out unwanted contaminants.

It is important to stress that the large scatter of the  $v_m$ - $\sigma_0$  relation is not a consequence of mixing low- and high-surface brightness galaxies. Although we cannot rigorously identify low-surface brightness galaxies in our sample with the material at hand, given the very bright luminosities of most of our sample it is highly improbable that a large fraction of them are low-surface brightness galaxies (see, e.g., Sprayberry et al. 1997).

The absence of a single, universal  $v_m$ - $\sigma_0$  correlation, in concert with the general consensus that the  $M_{\text{BH}}$ - $\sigma_0$  relation is tight, casts doubt on Ferrarese’s (2002) hypothesis that the halo mass is more fundamentally connected to the black hole mass than is the bulge mass. Judging from both direct dynamical searches of black holes (e.g., Magorrian et al. 1998; Kormendy 2004, and references therein) and the high detection rate of active nuclei in early-type galaxies (Ho et al. 1997; Ho 2004), the occupation fraction of black holes in bulges is very high, perhaps approaching unity. By contrast, the inverse may be true in late-type and dwarf galaxies. None has so far yielded a direct dynamical detection of a central black hole (Gebhardt et al. 2001; Merritt et al. 2001; Valluri et al. 2005), and nu-

clear activity is exceedingly rare (Ho et al. 1997; Ulvestad & Ho 2002), though not unknown<sup>7</sup> (Filippenko & Ho 2003; Barth et al. 2004, 2005; Greene & Ho 2004, 2007a, 2007b). Thus, with a few exceptions, central black holes, be they active or inactive, are associated almost exclusively with bulges, *not* halos. The very late-type spirals included in this study (sample 3) possess substantial rotation velocities ( $65 < v_m < 140 \text{ km s}^{-1}$ ) and correspondingly non-negligible halo masses but effectively no bulges (Böker et al. 2003): their central stellar velocity dispersion,  $13 < \sigma_0 < 34 \text{ km s}^{-1}$ , arises not from a bulge but a compact, nuclear star cluster (Kormendy & McClure 1993; Filippenko & Ho 2003; Walcher et al. 2005). If  $M_{\text{BH}}$  were more fundamentally linked with  $v_m$  than  $\sigma_0$ , we would expect these galaxies to possess black holes with  $M_{\text{BH}} \approx 2 \times 10^5$  to  $4 \times 10^6 M_\odot$  [using the  $v_m$ - $\sigma_0$  relation of Baes et al. (2003) and the  $M_{\text{BH}}$ - $\sigma_0$  relation of Tremaine et al. (2002)], and yet none but NGC 4395 is known for sure to contain a central black hole (Filippenko & Ho 2003). M33 (NGC 598) has the most stringent limit:  $M_{\text{BH}} < 1500 M_\odot$  (Gebhardt et al. 2001).

#### 4.2. Implications for Galaxy Formation

Discouraging as it may be as a black hole mass predictor, the  $v_m$ - $\sigma_0$  relation can be regarded as a useful, additional constraint on galaxy formation models. What factors determine the  $v_m/\sigma_0$  ratio in any given galaxy? Our study, in agreement with that of Courteau et al. (2007), shows that  $v_m/\sigma_0$  depends, at least in part, on the mass distribution within a galaxy. This is evident in the correlation between  $v_m/\sigma_0$  and three mutually related quantities that reflect the density profile of a galaxy, namely its Hubble type, bulge-to-disk ratio, and concentration index. The trends are systematic and statistically significant, but none of the correlations can be regarded as particularly tight, suggesting that  $v_m/\sigma_0$  probably depends on more than just the density profile alone. This can be anticipated from consideration of the collisionless Boltzmann equation for a stellar system in gravitational equilibrium, in which the rotation velocity and velocity dispersion at radius  $r$  are related by

$$v^2(r) = \sigma_r^2(r) \left[ -\frac{d \ln \rho(r)}{d \ln r} - \frac{d \ln \sigma_r^2(r)}{d \ln r} - 2 \left( 1 - \frac{\sigma_\theta^2}{\sigma_r^2} \right) \right]. \quad (6)$$

Here  $\sigma_r$  and  $\sigma_\theta$  are the velocity dispersions along the radial and tangential directions, and  $\rho$  is the stellar density profile. Following Courteau et al. (2007), we can recast this equation as

$$\frac{v_m}{\sigma_0} = \frac{v_m}{v_0} \left[ -\frac{d \ln \rho(r)}{d \ln r} - \frac{d \ln \sigma_r^2(r)}{d \ln r} - 2 \left( 1 - \frac{\sigma_\theta^2}{\sigma_r^2} \right) \right]^{1/2}, \quad (7)$$

where  $v_0$  denotes the rotation velocity in the inner part of the galaxy. The dependence of  $v_m/\sigma_0$  on the density profile enters directly through the first term in the brackets as well as through  $v_m/v_0$ , which depends on the shape of the rotation curve and hence on the detailed mass distribution of the galaxy (Rubin et al. 1978, 1985).

The challenge for galaxy formation models is not to explain why  $v_m/\sigma_0$  varies (as it is obvious from equation 7 that it should), but rather why galaxies in the local Universe populate the  $v_m$ - $\sigma_0$  plane in the manner observed. In this sense, we can

<sup>7</sup>Previous authors (Ferrarese 2002; Baes et al. 2003; Buyle et al. 2006) have used the apparent break down of the  $v_m$ - $\sigma_0$  relation at low velocities to infer that low-mass galaxies do not host central black holes. This is incorrect. Bona fide examples of active galactic nuclei with low-mass black holes in low-mass (even dwarf) galaxies *are* known. Although such objects are apparently rare, current search techniques introduce strong selection biases and preclude any definitive conclusions regarding their true space densities (Greene & Ho 2007a).

regard the distribution of galaxies on the  $v_m$ - $\sigma_0$  diagram as another local empirical boundary condition—much like other empirical galaxy scaling relations—that can be used to both guide and constrain theoretical models. Courteau et al. (2007), for example, attempted to reproduce, with limited success, the actual variation of  $v_m/\sigma_0$  with concentration index using the equilibrium disk-bulge-halo models of Widrow & Dubinski (2005).

#### 4.3. Origin of the Low- $v_m/\sigma_0$ Systems

One of the most notable features in the  $v_m$ - $\sigma_0$  diagram is the existence of a significant number of outliers with very low values of  $v_m/\sigma_0$  (*open triangles* in Fig. 2). As an operational definition, we have designated this population as those that deviate from the  $K_s$ -band Tully-Fisher relation toward the low- $v_m$  side by more than twice the rms scatter. This definition, though somewhat ad hoc, effectively isolates most of the members characterized by  $v_m/\sigma_0 \lesssim 1$ . Although the low- $v_m/\sigma_0$  objects comprise only 17% (132/792) of the total sample, they are nonetheless very intriguing because the kinematic measurements are robust. Some of these systems have rotation velocities as low as  $\sim 30 \text{ km s}^{-1}$ , and yet most are luminous, with  $M_{B_r} \approx -19$  to  $-21$  mag. Moreover, these galaxies have central stellar velocity dispersions as large as  $\sigma_0 \approx 100$ – $250 \text{ km s}^{-1}$ : it is impossible for a cold disk rotating this slowly to survive in such a dynamically hot system. The low- $v_m/\sigma_0$  outliers can be found in essentially all Hubble type bins included in our study, but they appear to be somewhat more prevalent among early-type (E and S0) galaxies: they make up 33% of the ellipticals, 40% of the S0s, and  $\sim 15\%$  to  $25\%$  of the spirals, depending on Hubble type.

Apart from their low  $v_m/\sigma_0$  ratios, the outliers do not stand out in any other obvious manner, at least with the data we readily have at our disposal (using data given in Tables 1 and 2 and as listed in Hyperleda). When normalized with respect to other galaxies of the same morphological type, they appear to be normal in terms of absolute magnitude, mean surface brightness (measured either at the effective radius or within  $\mu_B = 25 \text{ mag arcsec}^{-2}$ ), integrated broad-band colors ( $U-B$ ,  $B-V$ ,  $B-I$ ,  $B-K_s$ ), and H I content (either the total H I mass,  $M_{\text{H I}}$ , or the H I mass normalized to the  $B$ -band luminosity,  $M_{\text{H I}}/L_B$ ). Among the disk galaxies in the sample, 56% are classified as barred, to be compared with 42% for the kinematically normal sample; it is unclear if the marginal excess of barred galaxies in the former sample is statistically significant. Other than the indirect effect of the morphology-density relation (e.g., Dressler 1980), no obvious trends with environment exist, although except for noting cluster membership we did not attempt to quantify the environment in any rigorous manner.

How might a luminous galaxy with a sizable hot spheroidal component have such kinematically cold neutral hydrogen? The first and most obvious possibility is that we have severely misjudged the inclination correction to the H I line width. Recall that the inclinations were derived from the axial ratios of the *stellar* isophotes, which implicitly assumes that the H I and stars are coaligned. If the gas and the stars are significantly misaligned, then the optically derived inclination angles may either overestimate or underestimate the inclination correction for the H I line width, depending on the sense of the misalignment. This then leads to inferred rotational velocities that are either too large or too small, with about equal probability. This effect must occur at some level, as galaxies with H I disks with varying degrees of misalignment are well-known, the most dra-

matic examples being polar ring systems, in which the gaseous and stellar disks are exactly orthogonal to one another. That this effect does occur in our sample can be seen in the Tully-Fisher diagrams shown in Figure 3: most galaxies cluster around a central ridgeline, but a significant number of objects deviate both to the low-velocity and high-velocity side of the ridgeline. A crucial point to note, however, is that the scatter is not symmetric: there is an *excess* of low-velocity sources compared to high-velocity sources. Moreover, the absolute deviation from the Tully-Fisher ridgeline is more extreme for the low-velocity objects than the high-velocity objects. Although H I disk misalignment may account for some of the low- $v_m/\sigma_0$  objects, this is not the whole story.

The asymmetric distribution of the Tully-Fisher outliers compels us to conclude that the H I in at least some of these objects must reside in a truly *dynamically unrelaxed* configuration with respect to the stellar gravitational potential. Three possibilities come to mind. First, the H I gas may be strongly disturbed as a result of tidal interactions, or perhaps distributed in tidal tails formed in the aftermath of a galaxy-galaxy merger. From optical studies of close pairs and interacting galaxies, Barton et al. (2001) and Kannappan & Barton (2004) discuss how asymmetric and truncated rotation curves can generate strong offsets in the Tully-Fisher relation. While this effect might account for some fraction of the outliers, recall that during our sample selection we have purposefully excluded galaxies with close companions and obvious morphological peculiarities. Thus, this cannot offer a viable solution to the problem at hand.

Second, perhaps the H I owes its kinematic anomaly to a large-scale galactic outflow, driven either by strong nuclear activity or a global starburst. We also consider this possibility to be untenable. The few galaxies with luminous active galactic nuclei or starbursts in our study (e.g., NGC 1068, NGC 3079, NGC 4051)—the most promising candidates for this scenario—belong, in fact, to the kinematically normal sample, exactly the opposite of what is expected. Furthermore, although we do not have uniform data to estimate star formation rates for the entire sample, the similarity in the broad-band optical and near-infrared colors of the two groups strongly suggests that their star formation rates are not grossly dissimilar. Lastly, it is worth remarking that the amount of neutral gas involved is quite substantial. The median H I mass for the low- $v_m/\sigma_0$  sample ranges from  $3 \times 10^8 M_\odot$  for the S0s to  $\sim 1 \times 10^9 M_\odot$  for the Es,  $2 \times 10^9 M_\odot$  for Sa spirals, and  $\sim 1 \times 10^{10} M_\odot$  for spirals of type Sb and later. Without detailed mapping we do not know precisely how much of the gas actually resides in the low-velocity component, but for it to markedly affect the integrated profile to the degree observed, the fraction of the total mass involved cannot be that miniscule. It seems doubtful that nuclear outflows or galactic fountains can perturb such a large quantity of gas. In NGC 891 (Swaters et al. 1997) and NGC 2403 (Fraternali et al. 2002), two of the best-studied spirals whose kinematically anomalous H I has been interpreted as possibly having a galactic fountain origin, the amount of gas affected is  $\sim \text{few} \times 10^8 M_\odot$ , roughly 10% of the total H I mass. Moreover, this material rotates only a few tens of  $\text{km s}^{-1}$  slower than the gas in the plane, nowhere near as extreme as some of our objects.

The final and, we believe, most likely possibility is that the dynamically unrelaxed H I traces material acquired from an external source, in the form of a minor merger with a gas-rich dwarf galaxy, capture of fallback material from incomplete con-

version of gas to stars after a major merger, or cold accretion from primordial clouds. Past studies of early-type galaxies have long invoked an external origin to account for the unusual properties of the neutral hydrogen in these systems, including the frequent detection of morphological and kinematic misalignments between the H I and stars (e.g., Raimond et al. 1981; van Gorkom et al. 1986; van Driel & van Woerden 1991; Oosterloo et al. 2002, 2007; Noordermeer et al. 2005; Morganti et al. 2006) and the apparent decoupling between the H I and stellar mass (Knapp et al. 1985; Wardle & Knapp 1986). In this sense, our results for E and S0 galaxies could have been anticipated. More surprising is that the same phenomenon persists well into the spiral sequence, to Hubble types as late as Scd. The incidence of low- $v_m/\sigma_0$  objects does decrease toward later Hubble types, but this may be an artifact of dilution by the intrinsically much larger H I content in these gas-rich systems. If, for the sake of argument, external accretion provides a baseline supply of  $10^8 M_\odot$  of H I to all sizable galaxies, irrespective of Hubble type or environment, this kinematically anomalous component would constitute a significantly larger fraction of the total H I budget in an E or S0 galaxy ( $\sim 20\% - 50\%$ ) than in an Sb or Sc galaxy ( $\sim 1\% - 5\%$ ), rendering it much more subtle to detect in the latter.

Notwithstanding the apparent similarity between early-type and spiral galaxies, the origin of the kinematically anomalous gas may be very different in these two classes of objects. The characteristically denser environment around ellipticals and at least some S0 galaxies sets a natural stage for interaction or merger-induced processes to play a more central role than in later-type galaxies. Spirals, on the other hand, may have access to another channel of gas supply—“cold accretion.” In numerical simulations of galaxy formation, accretion of cold gas along filamentary structures dominates the growth of lower-mass galaxies at high redshifts and in low-density environments today (Kereš et al. 2005; Macció et al. 2006). Despite the purported cosmological importance of this process, there has been very limited observational evidence to support it. A long-standing argument that spiral galaxies may accrete appreciable amounts of gas directly from the intergalactic medium comes from considerations of the high-velocity clouds in the Milky Way (Oort 1970; Wakker et al. 1999) and their probable extragalactic counterparts (van der Hulst & Sancisi 1988; Thilker et al. 2004). Using a blunt but effective tool, namely the  $v_m - \sigma_0$  diagram in combination with the Tully-Fisher relation, this study has highlighted a population of galaxies with kinematically anomalous H I that appear to be excellent candidates for undergoing cold accretion. Deep aperture synthesis observations of *isolated* spirals are needed to confirm or reject this hypothesis; to our knowledge, none of the candidates from our list has been studied in this way. The selection by environment is important in order to distinguish a true cold accretion event from other sources of gas infall. For example, the Sc spiral NGC 4254, one of the low- $v_m/\sigma_0$  galaxies in our sample, has long been known to possess kinematically distorted H I, but its location in the Virgo cluster suggests that its peculiar gas kinematics and distribution most likely arose from a tidal encounter with another galaxy or from interactions with the intracluster medium (e.g., Phookun & Mundy 1995; Vollmer et al. 2005).

We reinvestigate the relation between the maximum rotation velocity of the disk and the central stellar velocity dispersion of the bulge in order to evaluate the claim that these two quantities are tightly correlated and independent of galaxy type. Making use of integrated H I line widths to estimate  $v_m$  and an expanded database of  $\sigma_0$  values augmented by new measurements from SDSS, our sample contains 792 galaxies, almost a factor of 5 larger than any past study. Contrary to previous reports, we find that the  $v_m - \sigma_0$  relation contains significant intrinsic scatter, and that the ratio  $v_m/\sigma_0$  varies systematically with Hubble type, bulge-to-disk ratio, and light concentration. The density profile of a galaxy plays a major role in determining  $v_m/\sigma_0$ , although the large residual scatter suggests that the kinematic structure of the galaxy also matters. Extreme late-type spirals that lack a clear bulge but contain a central nuclear star cluster deviate dramatically from the  $v_m - \sigma_0$  relation. The observed distribution of galaxies on the  $v_m - \sigma_0$  plane serves as an important local boundary condition to constrain models of galaxy formation.

The lack of a tight  $v_m - \sigma_0$  relation removes the principal motivation for substituting the halo for the bulge as the galaxy component most closely linked with the central black hole. Although  $v_m$  is inferior to  $\sigma_0$  as a predictor of black hole mass, the  $M_{\text{BH}} - v_m$  relation remains a useful tool in instances when  $\sigma_0$  is too difficult to measure.

To constrain the intrinsic distribution of  $v_m/\sigma_0$  for any given Hubble type, we constructed a  $K_s$ -band Tully-Fisher relation for the sample using near-infrared photometry from 2MASS. The  $K_s$ -band Tully-Fisher relation is essentially invariant, for morphological types ranging from elliptical galaxies to late-type spirals. This exercise revealed an unexpected population of outliers characterized by having anomalously low rotation velocities for their luminosity, and correspondingly low  $v_m/\sigma_0$  values. While misaligned H I disks and tidal tails may account for some of these low- $v_m/\sigma_0$  objects, we argue that the majority of them must have acquired their low-velocity, dynamically unrelaxed gas through external capture or cold accretion from the intergalactic medium.

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## APPENDIX

## COMPARISON OF LITERATURE DATA

*Stellar Velocity Dispersions*

Among the 293 galaxies from our original sample 1 selected from Hyperleda (see §2), 37 have independent  $\sigma_0$  measurements given in the SDSS database. Figure 8a compares the velocity dispersion data in common. The quoted error bars from SDSS are significantly smaller than those given in Hyperleda, but it is not clear how realistic the SDSS error values are. Although the scatter is large, on average the SDSS velocity dispersions tend to be smaller than those given in Hyperleda; for this comparison sample, we find  $\langle \sigma_0(\text{SDSS})/\sigma_0(\text{Hyperleda}) \rangle = 0.89 \pm 0.30$  (Fig. 8b). Because the Hyperleda velocity dispersion scale has been cross-calibrated using multiple measurements of bright galaxies (following the procedure of McElroy 1995), we believe that the Hyperleda values are more reliable. Consequently, we have increased the velocity dispersions for the SDSS objects (sample 2) by a factor of 1.12.

*Rotation Velocities*

Reliable integrated H I line widths are available for 93 of the galaxies for which Courteau et al. (2007) compiled rotation velocities measured from extended optical rotation curves. A comparison of the two quantities is given in Figure 9a. There is generally good agreement between the two sets of measurements, but on average the H I-based velocities are smaller by a factor of 1.09, with a standard deviation of 0.22. Given that our values of  $v_m$  depend on a specific calibration between H I line width and rotation velocity and a specific formalism for correcting the H I line width for turbulent broadening (see §2), this level of agreement is quite satisfactory. In any case, only a small fraction of our objects (4%; total of 33 objects from samples 4b and 4c) come from Courteau et al.’s compilation. Closer inspection reveals a number of prominent outliers, particularly toward low H I velocities. Figure 9b, which plots the ratio of H I to optical velocities as a function of morphological type, illustrates that early-type ( $T \lesssim 0$ , or E and S0) galaxies show the greatest tendency for the H I line widths to underpredict the optical rotation velocities. The implications of this trend are further discussed in §4.3.

We remarked in §2 that Hyperleda’s procedure of homogenizing H I line widths does not take into account the possibility of source confusion. We illustrate this effect in Figure 10, where the Hyperleda velocities are compared directly with our rederived velocities. Although most of the points agree reasonably well for  $v_m \gtrsim 150\text{--}200 \text{ km s}^{-1}$ , note that at lower velocities the Hyperleda values tend to be systematically and significantly (up to  $\sim 40\%$ ) larger than ours. We attribute this effect to source confusion in the Hyperleda average. Since the relative radial velocities of neighboring galaxies are generally larger than the internal velocity of any constituent galaxy, source confusion naturally leads to systematically larger line widths.

*Inclination Corrections*

In the course of tracking down the cause of highly discrepant values of  $v_m/\sigma_0$ , we noticed that some of the inclination angles listed in Hyperleda are incorrect. For instance, the nearby, well-resolved late-type spiral NGC 4395 is listed in Hyperleda as having  $b/a = 0.37$  or  $i = 90^\circ$ , whereas the Third Reference Catalogue of Bright Galaxies (RC3; de Vaucouleurs et al. 1991) gives  $b/a = 0.83$ , which corresponds to  $i = 38^\circ$ . Simple inspection of the Digital Sky Survey images clearly shows that NGC 4395 is far from edge-on. The S0 galaxy NGC 3106 provides another example: Hyperleda lists  $b/a = 0.30$  and  $i = 90^\circ$ , while the RC3 gives  $b/a = 1.0$ , consistent with being nearly face-on, again in agreement with visual examination of the optical image of the galaxy. While most galaxies in our sample show less blatant disagreement, we find that there is a general tendency for Hyperleda to underestimate the axial ratio ( $b/a$ ), and hence to *overestimate* the inclination angle. This is illustrated in Figure 11, where we use the RC3 as a reference. Note the systematic difference between the two databases, and that the discrepancy is especially pronounced for barred galaxies. While in principle there is no a priori reason to trust the RC3 more than Hyperleda, our systematic inspection of images for our sample (e.g., the two cases mentioned above) leads us to believe that the axial ratios given in the former are more reliable than those in the latter.

It is unclear why the axial ratios listed in Hyperleda are systematically lower. In the case of barred galaxies, which show the largest systematic deviations, it is conceivable that the high surface brightness of the bar may have biased the apparent ellipticity of the isophotes used to deduce the axial ratio. In some instances, we noted that the final axial ratio adopted in Hyperleda does not, it seems, correspond to the *B*-band data actually tabulated in the database, from which the axial ratio (parameter  $\log r_{25}$ ) supposedly was derived. Instead, it appears that the adopted axial ratio included in its average size measurements from near-infrared bandpasses. In other cases (e.g., PGC 18506), the database does not, in fact, list any *B*-band measurements at all, even though  $\log r_{25}$  strictly speaking is said to be derived from *B*-band data. Since features such as bars tend to be more prominent in redder bandpasses, and shallow near-infrared surveys (e.g., DENIS; Paturel et al. 2005) are less effective at picking up the low-surface brightness outer regions of the disk component, barred galaxies will generally appear to have a higher ellipticity than if measured from deeper *B*-band photometry. This probably contributes to the effect seen in Figure 11.

In light of these complications with the Hyperleda axial ratios, we decided to collect our own values from the literature (see Table 1). Whenever possible, we give preference to the large body of uniform measurements given in the RC3. We use these axial ratios to rederive inclination angles, following the same precepts adopted in Hyperleda (Paturel et al. 1997). The inclination angles are then used to correct the H I line widths, as well as to estimate internal extinctions for the absolute magnitudes, again following the procedures used in Hyperleda.

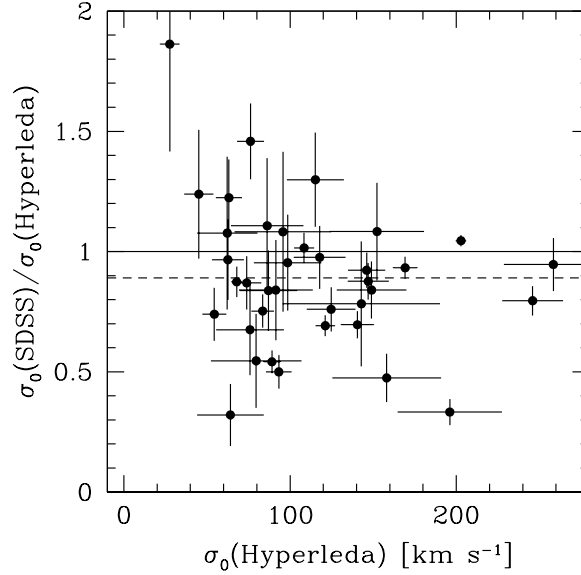


FIG. 8.— Comparison of central velocity dispersions for 37 objects contained in both the Hyperleda sample (sample 1) and the SDSS sample (sample 2). On average  $\langle \sigma_0(\text{SDSS})/\sigma_0(\text{Hyperleda}) \rangle = 0.89 \pm 0.30$ .

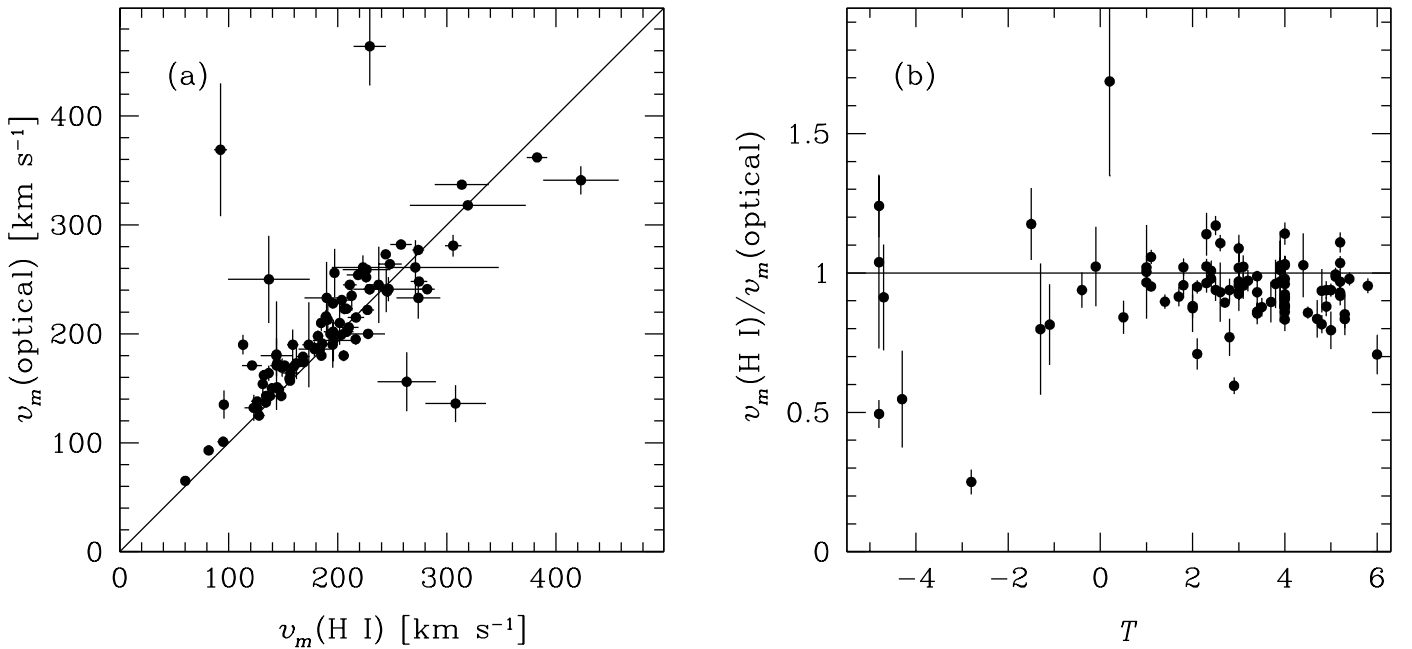


FIG. 9.— (a) Comparison of rotational velocities obtained from integrated H I profiles with those measured from resolved optical rotation curves, as compiled for 93 galaxies in the sample of Courteau et al. (2007). (b) Ratio of rotation velocities derived from H I profile versus resolved optical rotation curves as a function of morphological type. Note the strong disagreement for early-type ( $T \lesssim 0$ ) systems.

#### REFERENCES

- Adelman-McCarthy, J. K., et al. 2007, *ApJS*, submitted
- Baes, M., Buyle, P., Hau, G. K. T., & Dejonghe, H. 2003, *MNRAS*, 341, L44
- Baes, M., Dejonghe, H., Buyle, P., Ferrarese, L., & Gentile, G. 2004, in *IAU Symp. 222, The Interplay among Black Holes, Stars and ISM in Galactic Nuclei*, ed. T. Storchi-Bergmann, L. C. Ho, & H. R. Schmitt (Cambridge: Cambridge Univ. Press), 25
- Baldwin, J. E., Lynden-Bell, D., & Sancisi, R. 1980, *MNRAS*, 193, 313
- Balkowski, C., & Chamaraux, P. 1981, *A&A*, 97, 223
- . 1983, *A&AS*, 51, 331
- Barnes, D. G., Staveley-Smith, L., Webster, R. L., & Walsh, W. 1997, *MNRAS*, 288, 307
- Barth, A. J., Greene, J. E., & Ho, L. C. 2005, *ApJ*, 619, L151
- Barth, A. J., Ho, L. C., Rutledge, R. E., & Sargent, W. L. W. 2004, *ApJ*, 607, 90
- Barton, E. J., Geller, M. J., Bromley, B. C., van Zee, L., & Kenyon, S. J. 2001, *AJ*, 121, 625
- Bell, E. F., & de Jong, R. S. 2001, *ApJ*, 550, 212
- Bernardi, M., et al. 2003, *AJ*, 125, 1849
- Bessell, M. S. 2005, *ARA&A*, 43, 293

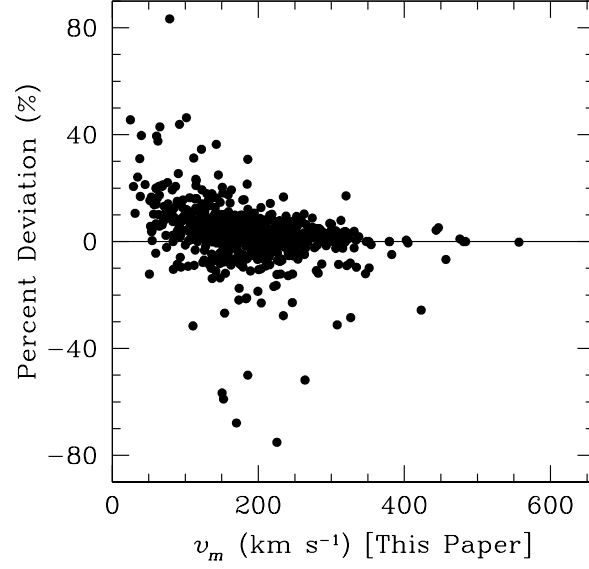


FIG. 10.— Comparison of rotational velocities listed in Hyperleda with those rederived in this paper using our own selection of H I line widths. The ordinate shows the percent deviation between the old and new values.

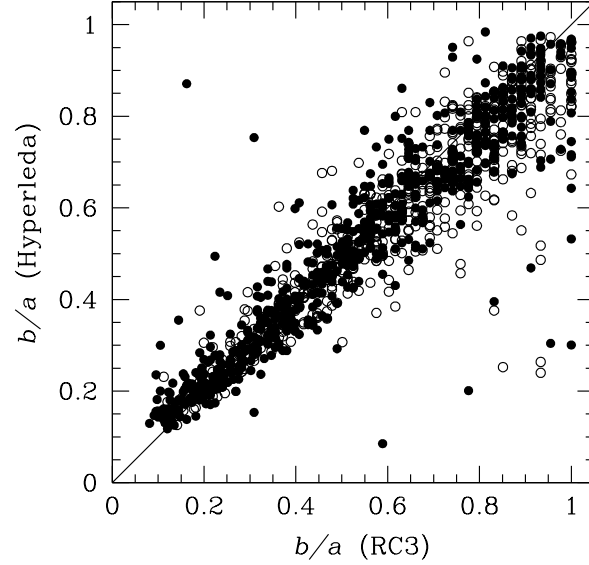


FIG. 11.— Comparison of axial ratios ( $b/a$ ) listed in Hyperleda with those given in the RC3. The ratio of semi-minor to semi-major isophotal diameter is measured at a surface brightness of  $\mu = 25$  mag arcsec $^{-2}$  in the  $B$  band. Unbarred and barred galaxies are denoted by solid and open points, respectively. The solid line marks a one-to-one correspondence.

Bicay, M. D., & Giovanelli, R. 1986a, *AJ*, 91, 705

———. 1986b, *aj*, 91, 732

———. 1987, *aj*, 93, 1326

Biegging, J. H., & Biermann, P. 1977, *A&A*, 60, 361

Binggeli, B., Sandage, A. R., & Tammann, G. A. 1985, *AJ*, 90, 1681

Böker, T., Stanek, R., & van der Marel, R. P. 2003, *AJ*, 125, 1073

Böker, T., van der Marel, R. P., Laine, S., Rix, H.-W., Sarzi, M., Ho, L. C., & Shields, J. C. 2002, *AJ*, 123, 1389

Bosma, A. 1979, Ph.D. Thesis, Univ. Groningen

———. 1981, *AJ*, 86, 1825

Bothun, G. D., Aaronson, M., Schommer, B., Huchra, J., & Mould, J. 1984, *ApJ*, 278, 475

Bothun, G. D., Aaronson, M., Schommer, B., Mould, J., Huchra, J., & Sullivan, W. T., III 1985, *ApJS*, 57, 423

Bottinelli, L., & Gouguenheim, L. 1977, *A&A*, 60, L23

———. 1979, *A&A*, 76, 176

Bottinelli, L., Gouguenheim, L., & Paturel, G. 1980, *A&A*, 88, 32

———. 1982, *A&A*, 113, 61

Bottinelli, L., Gouguenheim, L., Paturel, G., & de Vaucouleurs, G. 1983, *A&A*, 118, 4

Bottinelli, L., Gouguenheim, L., Paturel, G., & Teerikorpi, P. 1995, *A&A*, 296, 64

Bottinelli, L., Gouguenheim, L., Theureau, G., Coudreau, N., & Paturel, G. 1999, *A&AS*, 135, 429

Bregman, J. N., Hogg, D. E., & Roberts, M. S. 1992, *ApJ*, 387, 484

Bregman, J. N., & Roberts, M. S. 1988, *ApJ*, 330, L93

Broeils, A. H., & Rhee, M.-H. 1997, *A&A*, 324, 877

Burstein, D., Krumm, N., & Salpeter, E. E. 1987, *AJ*, 94, 883

Buyle, P., Ferrarese, L., Gentile, G., Dejonghe, H., Baes, M., & Klein, U. 2006, *MNRAS*, 373, 700

Chamaraux, P., Balkowski, C., & Fontanelli, P. 1987, *A&AS*, 69, 263

- Chamaraux, P., Cayatte, V., Balkowski, C., & Fontanelli, P. 1990, *A&A*, 229, 340
- Chengalur, J. N., Salpeter, E. E., & Terzian, Y. 1994, *AJ*, 107, 1984
- Courteau, S. 1997, *AJ*, 114, 2402
- Courteau, S., McDonald, M., Widrow, L. M., & Holtzman, J. 2007, *ApJ*, 655, L21
- Davies, R. D., & Lewis, B. M. 1973, *MNRAS*, 165, 231
- Davis, L. E., & Seaquist E. R. 1983, *ApJS*, 53, 269
- Dean, J. F., & Davies, R. D. 1975, *MNRAS*, 170, 503
- Dell'Antonio, I., Bothun, G. D., & Geller, M. J. 1996, *AJ*, 112, 1759
- De Rijcke, S., Zeilinger, W. W., Hau, G. K. T., Prugniel, P., & Dejonghe, H. 2007, *ApJ*, 659, 1172
- de Vaucouleurs, G., de Vaucouleurs, A., Corwin, H. G., Jr., Buta, R. J., Paturel, G., & Fouqué, R. 1991, *Third Reference Catalogue of Bright Galaxies (New York: Springer) (RC3)*
- Dickel, J. R., & Rood, H. J. 1978, *ApJ*, 223, 391
- Doi, M., Fukugita, M., & Okamura, S. 1993, *MNRAS*, 264, 832
- Dressler, A. 1980, *ApJ*, 236, 351
- Dutton, A. A., van den Bosch, F. C., Dekel, A., & Courteau, S. 2007, *ApJ*, 654, 27
- Eder, J., Giovanelli, R., & Haynes, M. P. 1991, *AJ*, 102, 572
- Faber, S. M., & Jackson, R. E. 1976, *ApJ*, 204, 668
- Fall, S. M. 1987, in *Nearly Normal Galaxies*, ed. S. M. Faber (New York: Springer), 326
- Ferrarese, L. 2002, *ApJ*, 578, 90
- Ferrarese, L., & Merritt, D. 2000, *ApJ*, 539, L9
- Filippenko, A. V., & Ho, L. C. 2003, *ApJ*, 588, L13
- Fisher, J. R., & Tully, R. B. 1981, *ApJS*, 47, 139
- Fontanelli, P. 1984, *A&A*, 138, 8
- Fosbury, R. A. E., Mebold, U., Goss, W. M., & Dopita, M. A. 1978, *MNRAS*, 183, 549
- Fouqué, R., Bottinelli, L., Gougouenheim, L., & Paturel, G. 1990, *ApJ*, 349, 1
- Franx, M. 1993, in *IAU Symp. 153, Galactic Bulges*, ed. H. Dejonghe & H. J. Habing (Dordrecht: Kluwer), 243
- Fraternali, F., van Moorsel, G., Sancisi, R., & Oosterloo, T. 2002, *AJ*, 123, 3124
- Freudling, W. 1995, *A&AS*, 112, 429
- Freudling, W., Haynes, M. P., & Giovanelli, R. 1988, *AJ*, 96, 1791
- . 1992, *ApJS*, 79, 157
- Fukugita, M., Shimasaku, K., & Ichikawa, T. 1995, *PASP*, 107, 945
- García, A. M., Bottinelli, L., Garnier, R., Gougouenheim, L., & Paturel, G. 1994, *A&AS*, 107, 265
- García-Barreto, J. A., Downes, D., & Huchtmeier, W. K. 1994, *A&A*, 288, 705
- Gavazzi, G. 1987, *ApJ*, 320, 96
- Gebhardt, K., et al. 2000, *ApJ*, 539, L13
- . 2001, *AJ*, 122, 2469
- Gerhard, O. E., Kronawitter, A., Saglia, R. P., & Bender, R. 2001, *AJ*, 121, 1936
- Giovanardi, C., Krumm, N., & Salpeter, E. E. 1983, *AJ*, 88, 1719
- Giovanardi, C., & Salpeter, E. E. 1985, *ApJS*, 58, 623
- Giovanelli, R., Avera, E., & Karachentsev, I. D. 1997, *AJ*, 114, 122
- Giovanelli, R., Chincarini, L., & Haynes, M. P. 1981, *ApJ*, 247, 383
- Giovanelli, R., & Haynes, M. P. 1983, *AJ*, 88, 881
- . 1985a, *ApJ*, 292, 404
- . 1985b, *AJ*, 90, 2445
- . 1993, *AJ*, 105, 1271
- Greene, J. E., & Ho, L. C. 2004, *ApJ*, 610, 722
- . 2006, *ApJ*, 641, 117
- . 2007a, *ApJ*, in press (astro-ph/0705.0020)
- . 2007b, submitted
- Haynes, M. P. 1981, *AJ*, 86, 1126
- Haynes, M. P., & Giovanelli, R. 1984, *AJ*, 89, 758
- . 1991a, *AJ*, 102, 841
- . 1991b, *ApJS*, 77, 331
- Haynes, M. P., Giovanelli, R., Chamaraux, P., da Costa, L. N., Freudling, W., Salzer, J. J., & Wegner, G. 1999, *AJ*, 117, 2039
- Haynes, M. P., Giovanelli, R., Herter, T., Vogt, N. P., Freudling, W., Maia, M. A. G., Salzer, J. J., & Wegner, G. 1997, *AJ*, 113, 1197
- Haynes, M. P., Giovanelli, R., Starosta, B. M., & Magri, C. 1988, *AJ*, 95, 606
- Haynes, M. P., Herter, T., Barton, A. S., & Benensohn, J. S. 1990, *AJ*, 99, 1740
- Haynes, M. P., van Zee, L., Hogg, D. E., Roberts, M. S., & Maddalena, R. J. 1998, *AJ*, 115, 62
- Heckman, T. M., & Balick, B., & Sullivan, W. T. 1978, *ApJ*, 224, 745
- Heckman, T. M., Kauffmann, G., Brinchmann, J., Charlot, S., Tremonti, C., & White, S. D. M. 2004, *ApJ*, 613, 109
- Heiles, C., et al. 2000, *Arecibo Technical and Operations Memo 2000-04*
- Helou, G., Giovanardi, C., Salpeter, E. E., & Krumm, N. 1981, *ApJS*, 46, 267
- Helou, G., Hoffman, G. L., & Salpeter, E. E. 1984, *ApJS*, 55, 433
- Hewitt, J. N., Haynes, M. P., & Giovanelli, R. 1983, *AJ*, 88, 272
- Ho, L. C. 2004, in *Carnegie Observatories Astrophysics Series, Vol. 1: Coevolution of Black Holes and Galaxies*, ed. L. C. Ho (Cambridge: Cambridge Univ. Press), 292
- Ho, L. C., Darling, J., & Greene, J. E. 2007a, *ApJS*, submitted
- . 2007a, *ApJ*, submitted
- Ho, L. C., Filippenko, A. V., & Sargent, W. L. W. 1997, *ApJ*, 487, 568
- Hoffman, G. L., Helou, G., & Salpeter, E. E. 1984, *ApJS*, 55, 433
- Hoffman, G. L., Lewis, B. M., Helou, G., Salpeter, E. E., & Williams, H. L. 1989, *ApJS*, 69, 55
- Hoffman, G. L., Lewis, B. M., Salpeter, E. E. 1995, *ApJ*, 441, 28
- Hopp, U., Kuhn, B., Thiele, U., Birkle, K., Elsasser, H., & Kovachev, B. 1995, *A&AS*, 109, 537
- Hubble, E. 1926, *ApJ*, 64, 321
- Huchtmeier, W. K. 1973, *A&A*, 22, 91
- . 1982, *A&A*, 110, 121
- Huchtmeier, W. K., Hopp, U., & Kuhn, B. 1997, *A&A*, 319, 67
- Huchtmeier, W. K., & Richter, O. G. 1985, *A&A*, 149, 118
- . 1987, *A&AS*, 63, 323
- Huchtmeier, W. K., Sage, L. J., & Henkel, C. 1995, *A&A*, 300, 675
- Huchtmeier, W. K., & Seiradakis, J. H. 1985, *A&A*, 143, 216
- Impey, C., Burkholder, V., & Sprayberry, D. 2001, *AJ*, 122, 2341
- Irwin, J. A., & Seaquist, E. R. 1991, *ApJ*, 371, 111
- Jørgensen, I., Franx, M., & Kjaergaard, P. 1995, *MNRAS*, 276, 1341
- Kannappan, S. J., & Barton, E. J. 2004, *AJ*, 127, 2694
- Karachentsev, I. D., et al. 2003, *A&A*, 404, 93
- Kereš, D., Katz, N., Weinberg, D. H., & Davé, R. 2005, *MNRAS*, 363, 2
- Knapp, G. R., Faber, S. M., & Gallagher, J. S. 1978, *AJ*, 83, 11
- Knapp, G. R., Kerr, F. J., & Henderson, A. P. 1979, *ApJ*, 234, 448
- Knapp, G. R., Turner, E. L., & Cunniffe, P. E. 1985, *AJ*, 90, 454
- Knapp, G. R., van Driel, W., & van Woerden, H. 1985, *A&A*, 142, 1
- Koribalski, B. S., et al. 2004, *AJ*, 128, 16
- Kormendy, J. 2004, in *Carnegie Observatories Astrophysics Series, Vol. 1: Coevolution of Black Holes and Galaxies*, ed. L. C. Ho (Cambridge: Cambridge Univ. Press), 1
- Kormendy, J., & Illingworth, G. 1983, *ApJ*, 265, 632
- Kormendy, J., & Gebhardt, K. 2001, in *The 20th Texas Symposium on Relativistic Astrophysics*, ed. H. Martel & J. C. Wheeler (Melville: AIP), 363
- Kormendy, J., & Kennicutt, R. C. 2004, *ARA&A*, 42, 603
- Kormendy, J., & McClure, R. D. 1993, *AJ*, 105, 1793
- Kraan-Korteweg, R. C., van Driel, W., Briggs, F., Binggeli, B., & Mostefaoui, T. I. 1999, *A&AS*, 135, 255
- Kronawitter, A., Saglia, R. P., Gerhard, O., & Bender, R. 2000, *A&AS*, 144, 53
- Krumm, N., & Salpeter, E. E. 1976, *ApJ*, 208, L7
- . 1980, *AJ*, 85, 1312
- Lee, M. G., Kim, M., Sarajedini, A., Geisler, D., & Wolfgang, G. 2002, *ApJ*, 565, 959
- Lewis, B. M. 1983, *AJ*, 88, 1695
- . 1987, *ApJS*, 63, 515
- Lewis, B. M., & Davies, R. D. 1973, *MNRAS*, 165, 213
- Lewis, B. M., Helou, G., & Salpeter, E. E. 1985, *ApJS*, 59, 151
- Lu, N. Y., Dow, M. W., Houck, J. R., Salpeter, E. E., & Lewis, B. M. 1990, *ApJ*, 357, 388
- Lu, N. Y., Hoffman, G. L., Groff, T., Roos, T., & Lamphier, C. 1993, *ApJS*, 88, 383
- Macció, A. V., Moore, B., & Stadel, J. 2006, *ApJ*, 636, L25
- MacGillivray, H. T., Beard, S. M., & Dodd, R. J. 1988, in *Astronomy from Large Databases: Scientific Objectives and Methodological Approaches (Garching: European Southern Observatory)*, 389
- Magorrian, J., et al. 1998, *AJ*, 115, 2285
- Magri, C. 1994, *AJ*, 108, 896
- Marconi, A., & Hunt, L. K. 2003, *ApJ*, 589, L21
- Martin, J. M., Bottinelli, L., Gougouenheim, L., & Dennefeld, M. 1991, *A&A*, 245, 393
- Mathewson, D. S., & Ford, V. L. 1996, *ApJS*, 107, 97
- Mathewson, D. S., Ford, V. L., & Buchhorn, M. 1992, *ApJS*, 81, 413
- Matthews, L. D., & van Driel, W. 2000, *A&AS*, 143, 421
- Matthews, L. D., van Driel, W., & Monnier-Ragaigne, D. 2001, *A&A*, 365, 1
- McElroy, D. B. 1995, *ApJS*, 100, 105
- Merritt, D., Ferrarese, L., & Joseph, C. L. 2001, *Science*, 293, 1116
- Mirabel, I. F., & Sanders, D. B. 1988, *ApJ*, 335, 104
- Mirabel, I. F., & Wilson, A. S. 1984, *ApJ*, 277, 92
- Morganti, R., et al. 2006, *MNRAS*, 371, 157
- Mould, J. R., et al. 1991, *ApJ*, 383, 467
- Mould, J. R., Akeson, R. L., Bothun, G. D., Han, M., Huchra, J. P., Roth, J., & Schommer, R. A. 1993, *ApJ*, 409, 14
- Navarro, J. F., & Steinmetz, M. 2000, *ApJ*, 538, 477
- Nelson, C. H., & Whittle, M. 1996, *ApJ*, 465, 96
- Nilson, P. 1973, *Uppsala General Catalogue of Galaxies (Uppsala: Astronomiska Observatoriet)*
- Noordermeer, E., van der Hulst, J. M., Sancisi, R., Swaters, R. A., & van Albada, T. S. 2005, *A&A*, 442, 137
- Nordgren, T. E., Chengalur, J. N., Salpeter, E. E., & Terzian, Y. 1998, *ApJS*, 115, 43
- Oort, J. H. 1970, *A&A*, 7, 381
- Oosterloo, T. A., Morganti, R., Sadler, E., Vergani, D., & Caldwell, N. 2002, *AJ*, 123, 729
- Oosterloo, T. A., Morganti, R., Sadler, E. M., van der Hulst, J. M., & Serra, P. 2007, *A&A*, 465, 787
- Oosterloo, T. A., & Shostak, S. 1993, *A&AS*, 99, 379
- Paturel, G., et al. 1997, *A&AS*, 124, 109
- Paturel, G., Fang, Y., Petit, C., Garnier, R., & Rousseau, J. 2000, *A&AS*, 146, 19



- Paturel, G., Petit, C., Prugniel, Ph., Theureau, G., Rousseau, J., Brouty, M., Dubois, P., & Cambr sy, L. 2003a, *A&A*, 412, 45
- Paturel, G., Theureau, G., Bottinelli, L., Goug nheim, L., Coudreau-Durand, N., Hallet, N., & Petit, C. 2003b, *A&A*, 412, 57
- Paturel, G., Vauglin, I., Petit, C., Borsenberger, J., Epchtein, N., Fouqu , P., & Mamon, G. 2005, *A&A*, 430, 751
- Peterson, S. D. 1979, *ApJS*, 40, 527
- Phookun, B., & Mundy, L. G. 1995, *ApJ*, 453, 154
- Pizagno, J., et al. 2007, *AJ*, in press (astro-ph/0608472)
- Pizzella, A., Corsini, E., Dalla Bont , E., Sarzi, M., Coccato, L., & Bertola, F. 2005, *ApJ*, 631, 785
- Raimond, E., Faber, S. M., Gallagher, J. S., III, & Knapp, G. R. 1981, *ApJ*, 246, 708
- Reif, K., Mebold, U., Goss, W. M., van Woerden, H., & Siegman, B. 1982, *A&AS*, 50, 451
- Richter, O.-G., & Huchtmeier, W. K. 1982, *A&A*, 109, 155
- . 1987, *A&AS*, 68, 427
- . 1991, *A&AS*, 87, 425
- Richter, O.-G., & Sancisi, R. 1994, *A&A*, 290, L9
- Rizzi, L., Bresolin, F., Kudritzki, R.-P., Gieren, W., Pietrzyski, G. 2006, *ApJ*, 638, 766
- Roberts, M. S. 1978, *AJ*, 83, 1026
- Roberts, M. S., & Haynes, M. P. 1994, *ARA&A*, 32, 115
- Rosenberg, J. L., & Schneider, S. E. 2000, *ApJS*, 130, 177
- Roth, J., Mould, J. R., & Davies, R. D. 1991, *AJ*, 102, 1303
- Roth, J., Mould, J. R., & Staveley-Smith, L. 1994, *AJ*, 108, 851
- Rubin, V. C., Burstein, D., Ford, W. K., Jr., & Thonnard, N. 1985, *ApJ*, 289, 81
- Rubin, V. C., Ford, W. K., Jr., & Thonnard, N. 1978, *ApJ*, 225, L107
- Rubin, V. C., Ford, W. K., Jr., Thonnard, N., Roberts, M. S., & Graham, J. A. 1976, *AJ*, 81, 687
- Salzer, J. J. 1992, *AJ*, 103, 385
- Schneider, S. E., Helou, G., Salpeter, E. E., & Terzian, Y. 1986, *AJ*, 92, 742
- Schneider, S. E., Thuan, T. X., Magri, C., & Wadiak, J. E. 1990, *ApJS*, 72, 245
- Schneider, S. E., Thuan, T. X., Mangum, J. G., & Miller, J. 1992, *ApJS*, 81, 5
- Schombert, J. M., Bothun, G. D., Schneider, S. E., & McGaugh, S. S. 1992, *AJ*, 103, 1107
- Shimasaku, K., et al. 2001, *AJ*, 122, 1238
- Skrutskie, M. F., et al. 2006, *AJ*, 131, 1163
- Sprayberry, D., Impey, C. D., Irwin, M. J., & Bothun, G. D. 1997, *ApJ*, 482, 104
- Staveley-Smith, L., & Davies, R. D. 1987, *MNRAS*, 224, 953
- . 1988, *MNRAS*, 231, 833
- Staveley-Smith, L., Davies, R. D., & Kinman, T. D. 1992, *MNRAS*, 258, 334
- Strateva, I., et al. 2001, *AJ*, 122, 1861
- Sulentic, J. W., & Arp, H. 1983, *AJ*, 88, 489
- Swaters, R. A., Sancisi, R., & van der Hulst, J. M. 1997, *ApJ*, 491, 140
- Theureau, G., et al. 2005, *A&A*, 430, 373
- Theureau, G., Bottinelli, L., Coudreau-Durand, N., Goug nheim, L., Hallet, N., Loulergue, M., Paturel G., & Teerikorpi, P. 1998, *A&AS*, 130, 333
- Thilker, D. A., Braun, R., Walterbos, R. A. M., Corbelli, E., Lockman, F. J., Murphy, E., & Maddalena, R. 2004, *ApJ*, 601, L39
- Thim, F., Hoessel, J. G., Saha, A., Claver, J., Dolphin, A., & Tammann, G. A. 2004, *AJ*, 127, 2322
- Thonnard, N. 1983, in *Internal Linematics and Dynamics of Galaxies*, ed. E. Athanassoula (Dordrecht: Reidel), 29
- Thuan, T. X., Lipovetsky V. A., Martin J. M., & Pustilnik S. A. 1999, *A&AS*, 139, 1
- Thuan, T. X., & Martin, G. E. 1981, *ApJ*, 247, 823
- Tift, W. G., & Cocke, W. J. 1988, *ApJS*, 67, 1
- Tremaine, S., et al. 2002, *ApJ*, 574, 740
- Tully, R. B., & Fisher, J. R. 1977, *A&A*, 54, 661
- Tully, R. R., & Fouqu , P. 1985, *ApJS*, 58, 67
- Ulvestad, J. S., & Ho, L. C. 2002, *ApJ*, 581, 925
- Valluri, M., Ferrarese, L., Merritt, D., & Joseph, C. L. 2005, *ApJ*, 628, 137
- van der Hulst, T., & Sancisi, R. 1988, *AJ*, 95, 1354
- van Driel, W., Arnaboldi, M., Combes, F., & Sparke, L. S. 2000, *A&AS*, 141, 385
- van Driel, W., Marcum, P., Gallagher, J. S., III, Wilcots, E., Guidoux, C., & Raga ne, D. M. 2001, *A&A*, 378, 370
- van Driel, W., Raga ne, D., Boselli, A., Donas, J., & Gavazzi, G. 2000, *A&AS*, 144, 463
- van Driel, W., & van Woerden, H. 1991, *A&A*, 243, 7
- van Gorkom, J. H., Knapp, G. R., Raimond, E., Faber, S. M., & Gallagher, J. S. 1986, *AJ*, 91, 791
- Verheijen, M. A. W. 2001, *ApJ*, 563, 694
- Verheijen, M. A. W., & Sancisi, R. 2001, *A&A*, 370, 765
- Vollmer, B., Huchtmeier, W., & van Driel, W. 2005, *A&A*, 439, 921
- Vorontsov-Velyaminov, B. A., Arkipova, V. P., & Kranogorskaja, A. A. 1963-1974, *Morphological Catalogue of Galaxies, Part I-V* (Moscow: Trudy Sternberg Stat. Astr. Inst.)
- Walcher, C. J., et al. 2005, *ApJ*, 618, 237 (err: 618, 237)
- Wakker, B. P., et al. 1999, *Nature*, 402, 388
- Wardle, M., & Knapp, G. R. 1986, *AJ*, 91, 23
- Wegner, G., Haynes, M. P., & Giovanelli, R. 1993, *AJ*, 105, 1251
- Whitmore, B. C., & Kirshner, R. P. 1981, *ApJ*, 250, 43A
- Whitmore, B. C., Schechter, P. L., & Kirshner, R. P. 1979, *ApJ*, 234, 68
- Whittle, M. 1992a, *ApJ*, 387, 109
- . 1992b, *ApJ*, 387, 121
- Widrow, L. M. & Dubinski, J. 2005, *ApJ*, 631, 838
- Williams, B. A. 1985, *ApJ*, 290, 462
- Williams, B. A., & Kerr, F. J. 1981, *AJ*, 86, 953
- Williams, B. A., & Rood, H. J. 1987, *ApJS*, 63, 265
- York, D. G., et al. 2000, *AJ*, 120, 1579
- Young, C. K., & Currie, M. J. 1998, *A&AS*, 127, 367
- Zasov, A. V., Petrochenko, L. N., & Cherepashchuk, A. M. 2005, *ARep*, 49, 362